

# Notes

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## 1 Important parameters

Here is a list of parameters that are used throughout the text.

- Geometrized unit system where  $c = G = 1$ , so that e.g.  $[L]_{\text{SI}} = [T]_{\text{SI}} = [M]_{\text{SI}} = [L]_{\text{GUS}}$

- Total mass  $M = m_1 + m_2$ . The secondary-to-primary mass ratio is  $q = \frac{m_2}{m_1}$ . The symmetric mass ratio is  $\eta = \frac{m_1 m_2}{M^2}$ . The reduced mass is  $\mu = M\eta = M \frac{q}{(1+q)^2}$ .
- Distance of nearest approach (pericenter distance)  $r_p$
- Semimajor axis  $a = \frac{r_p}{1-e}$  for an elliptic orbit with eccentricity  $e$
- The mean angular frequency (radians per unit time) is from Kepler's third law

$$\omega_{\text{orb}} = \sqrt{\frac{M}{a^3}}. \quad (1)$$

Note that the orbital period does not depend on the eccentricity.

- Orbital period  $T = 2\pi\omega_{\text{orb}}^{-1}$
- Vis-viva equation (valid for any Keplerian orbit)

$$v^2 = m_1 \left( \frac{2}{r} - \frac{1}{a} \right). \quad (2)$$

### 1.1 On (unbound) hyperbolic orbits

- Semi-major axis

$$-a = \frac{M}{v^2}$$

- Eccentricity

$$e^2 = 1 + \frac{b^2 v^4}{M^2}$$

- Pericenter distance

$$r_p = -a(e-1) = \frac{M}{v^2} \left[ \left( 1 + \frac{b^2 v^4}{M^2} \right)^{1/2} - 1 \right].$$

Here  $b$  is the impact parameter. For small relative velocities  $v$  this simplifies to

$$r_p \simeq \frac{b^2 v^2}{2M} \left( 1 - \frac{b^2 v^4}{4M^3} \right). \quad (3)$$

### 1.2 Bound binary in elliptic orbit

- Orbital energy of two orbiting bodies is the sum of their mutual potential energy and their total kinetic energy

$$E = M\eta \left( \frac{v^2}{2} - \frac{M}{r} \right) = -\frac{\eta M^2}{2a}. \quad (4)$$

- The absolute value of the orbital angular momentum is

$$J = \mu \sqrt{Ma(1-e^2)} = \mu \omega_{\text{orb}} a^2 \sqrt{1-e^2}. \quad (5)$$

- Eccentricity

$$e^2 = 1 + \frac{2EL^2}{M^2\mu^3} = 1 + \frac{2Ev^2b^2}{M^2\mu}. \quad (6)$$

- Escape velocity of a orbiting body at a radius  $r$  can be obtained from the vis-viva equation (2) by taking the limit as  $a \rightarrow \infty$

$$v_{\text{esc}} = \sqrt{\frac{2m_1}{r}}. \quad (7)$$

### 1.3 Evolution equations of $e$ and $a$

The evolution equations of the eccentricity and semi-major axis of a bound binary are obtained by differentiating equations (4) and (6),

$$\frac{d \log a}{dt} = \frac{1}{a} \frac{da}{dt} = -\frac{\dot{E}}{E} + \frac{2\dot{M}}{M} + \frac{\dot{\eta}}{\eta}, \quad (8)$$

and

$$\frac{de}{dt} = \frac{1-e^2}{2e} \left[ -\frac{2\dot{L}}{L} - \frac{\dot{E}}{E} + \frac{2\dot{M}}{M} - \frac{3\dot{\mu}}{\mu} \right]. \quad (9)$$

Under the assumption that  $\dot{M} = \dot{\mu} = 0$ , the last equation can be rewritten as

$$\frac{de}{dt} = \frac{a(1-e^2)}{e\mu M} \left[ \dot{E} - \frac{M^{1/2}}{a^{3/2}(1-e^2)^{1/2}} \dot{L} \right]. \quad (10)$$

Thus  $\dot{E} < 0$  is a negative contribution to  $\dot{e}$  and  $\dot{L} < 0$  is a positive contribution to  $\dot{e}$ .

## 2 Aspects of gravitational wave emission

### 2.1 Multipole expansion formalism

A good reference for details and derivations regarding the multipole expansion formalism of gravitational waves is [1].

In the wave zone, gravitational waves can be treated as linearised perturbations propagating on a flat background metric. This background metric can be characterized by a Minkowskiian coordinate system whose origin coincides with the source. In this coordinate frame the transverse and traceless part of the metric perturbation has then the form

$$h_{ij}^{TT} = \frac{1}{r} A_{ij}(t-r, \theta, \phi), \quad (11)$$

where  $A_{ij}$  is a traceless and transverse tensor varying in the wave zone rapidly in the radial direction but slowly in the transverse direction. The angular dependence of the radiation field  $A_{ij}$  can be decomposed into spin-2 tensor spherical harmonics. Because  $A_{ij}$  is traceless and transverse, it can contain only the TT

harmonics  $\mathbf{T}^{\text{E2},lm}$  and  $\mathbf{T}^{\text{B2},lm}$ . For  $l = 0$  and  $l = 1$  there are no TT harmonics. Therefore the radiation field has the form

$$h_{ij}^{TT} = \frac{1}{r} \sum_{l=2}^{\infty} \sum_{m=-l}^l \left[ {}^{(l)}I^{lm}(t-r) T_{ij}^{\text{E2},lm} + {}^{(l)}S^{lm}(t-r) T_{ij}^{\text{B2},lm} \right]. \quad (12)$$

The expansion coefficients  ${}^{(l)}I^{lm}$  and  ${}^{(l)}S^{lm}$  are the  $l$ th time derivative of the mass multipole moments  $I^{lm}$  and the current multipole moments  $S^{lm}$ . Accordingly, the leading order terms  $I^{2m}$  are called mass quadrupole contributions, terms associated with  $S^{2m}$  are called current quadrupole contributions, terms arising from  $I^{3m}$  are called mass octupole contributions, etc.

The explicit expression of  $I^{lm}$  is given by

$$I^{lm} = \frac{16\pi}{(2l+1)!!} \left( \frac{(l+1)(l+2)}{2l(l-1)} \right)^{1/2} \mathcal{G}_{A_l} \mathcal{Y}_{A_l}^{lm*}, \quad (13)$$

and  $S^{lm}$  has a similar expression which we however don't need throughout this work.

### 2.1.1 Energy loss

In the multipole formalism the total radiated power is given by

$$P = \frac{dE}{dt} = \frac{1}{32\pi} \sum_{l=2}^{\infty} \sum_{m=-l}^l \left\langle |{}^{(l+1)}I^{lm}|^2 + |{}^{(l+1)}S^{lm}|^2 \right\rangle. \quad (14)$$

In what follows, we only consider mass quadrupole radiation. This amounts to neglecting all contributions arising from  $S^{lm}$  and to neglecting contribution from  $I^{lm}$  for  $l > 2$ . If the source is non-relativistic and has a negligible self-gravity, we can express  $\mathcal{G}$  in terms of the Newtonian mass density  $\rho$

$$\mathcal{G}_{a_1 a_2} = \int d^3x \rho x_{a_1} x_{a_2}; \quad (15)$$

this expression is also known as the second mass moment. Then

$$I^{2m} = \frac{16\pi}{5\sqrt{3}} \int d^3x \rho \mathcal{Y}_{a_1 a_2}^{2m*} x_{a_1} x_{a_2} \quad (16)$$

$$\equiv \frac{16\pi}{5\sqrt{3}} \int d^3x \rho r^2 Y^{2m*}. \quad (17)$$

### 2.1.2 Angular momentum loss

In the multipole expansion formalism, the change in angular momentum of a system due to gravitational wave emission is given by

$$\frac{dL_j}{dt} = \sum_{l=2}^{\infty} \frac{(l+1)(l+2)}{(l-1)l!(2l+1)!!} \left\langle \epsilon_{j pq} {}^{(l)}\mathcal{G}_{p A_{l-1}} {}^{(l+1)}\mathcal{G}_{q A_{l-1}} \right\rangle \quad (18)$$

$$+ \sum_{l=2}^{\infty} \frac{4l^2(l+2)}{(l-1)(l+1)!(2l+1)!!} \left\langle \epsilon_{j pq} {}^{(l)}\mathcal{S}_{p A_{l-1}} {}^{(l+1)}\mathcal{S}_{q A_{l-1}} \right\rangle. \quad (19)$$

In the mass quadrupole approximation this reduces to

$$\frac{dL_j}{dt} = \frac{2}{5} \left\langle \epsilon_{j pq} {}^{(2)}\mathcal{G}_{pa} {}^{(3)}\mathcal{G}_{qa} \right\rangle. \quad (20)$$

## 2.2 Application to Keplerian orbit

In this section we calculate, for a Keplerian orbit and for all  $e \geq 0$ , the energy flux, angular momentum flux and energy spectrum resulting from gravitational wave emission.

### 2.2.1 Energy loss

We choose a coordinate system whose origin coincides with the center of mass of the system and we let the binary lie in the  $\theta = \pi/2$ -plane. The two masses can then be specified by  $(r_1 \cos \phi, r_1 \sin \phi)$  and  $(-r_2 \cos \phi, -r_2 \sin \phi)$  with  $r_i = \frac{\mu r}{m_i}$ . The problem is equivalent to a one body problem of a reduced mass orbiting about the total mass located at the center of mass. Thus

$$I^{2m} = \frac{16\pi}{5\sqrt{3}} \left[ m_1 \frac{\mu^2 r^2}{m_1^2} Y^{2m*} \left( \frac{\pi}{2}, \phi \right) + m_2 \frac{\mu^2 r^2}{m_2^2} Y^{2m*} \left( \frac{\pi}{2}, \phi + \pi \right) \right]. \quad (21)$$

The  $Y^{2\pm 1*} \left( \frac{\pi}{2}, \phi \right)$  terms vanish, so we get  $Y^{2m*} \left( \frac{\pi}{2}, \phi \right) = Y^{2m*} \left( \frac{\pi}{2}, \phi + \pi \right)$ . Thus

$$I^{2m} = \frac{16\pi}{5\sqrt{3}} \mu r^2 Y^{2m*} \left( \frac{\pi}{2}, \phi \right). \quad (22)$$

In the quadrupole approximation the power radiated by the system reduces from expression (14) to

$$P = \frac{1}{32\pi} \sum_{m=-2}^2 |(3)I^{2m}|^2 \quad (23)$$

This expression is also valid for hyperbolic orbits, therefore we omitted taking already the average at this stage.

The orbit equations

$$r = \frac{r_p(1+e)}{1+e \cos \phi}, \quad (24)$$

$$r^2 \frac{d\phi}{dt} = [M_{\text{tot}} r_p (1+e)]^{1/2}. \quad (25)$$

allow the calculation of the time derivatives of  $I^{2m}$ . Employing these identities and using the explicit expression of the spherical harmonics  $Y^{2m*}$ , the third time derivatives of  $I^{2m}$  read

$$\begin{aligned} (3)I^{20} &= \left( \frac{64\pi}{15} \right)^{1/2} \frac{\mu M_{\text{tot}}^{3/2}}{[r_p(1+e)]^{5/2}} (1+e \cos \phi)^2 e \sin \phi, \\ (3)I^{2-2} &= \left( \frac{32\pi}{5} \right)^{1/2} \frac{\mu M_{\text{tot}}^{3/2}}{[r_p(1+e)]^{5/2}} (1+e \cos \phi)^2 [-e \sin \phi - 4i(1+e \cos \phi)] e^{2i\phi}, \\ (3)I^{22} &= \left( (3)I^{2-2} \right)^*. \end{aligned}$$

The radiated power as a function of  $\phi$  along the orbit is then

$$P(\phi) = \frac{8}{15} \frac{\mu^2 M_{\text{tot}}^3}{[r_p(1+e)]^5} (1+e \cos \phi)^4 [e^2 \sin^2 \phi + 12(1+e \cos \phi)^2]. \quad (26)$$

Note that this expression is valid for all values of  $e \geq 0$ .

**Hyperbolic orbit  $e \geq 1$ :** The asymptotes of the hyperbolic orbit are given by  $\cos \psi = -1/e$ . Thus the total energy released by a binary on an hyperbolic orbit is

$$\begin{aligned} E &= \int_{-\psi}^{\psi} P(\phi) \frac{dt}{d\phi} d\phi \\ &= \frac{8}{15} \frac{\eta^2 M_{\text{tot}}^{9/2}}{(r(1+e))^{7/2}} \int_{-\psi}^{\psi} d\phi (1+e \cos \phi)^2 [e^2 \sin^2 \phi + 12(1+e \cos \phi)^2] \\ &= \frac{\eta^2 M_{\text{tot}}^{9/2}}{r_p^{7/2} (1+e)^{7/2}} \varrho(e), \end{aligned}$$

where

$$\begin{aligned} \varrho(e) &= \frac{1}{180} [(12(96 + 292e^2 + 37e^4)\phi + 48e(96 + 73e^2) \sin \phi \\ &\quad + 24e^2(71 + 12e^2) \sin 2\phi + 368e^3 \sin 3\phi + 33e^4 \sin 4\phi]_{-\psi}^{\psi} \\ &= \frac{64}{5} \left[ \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) \cos^{-1} \left(-\frac{1}{e}\right) + \frac{301}{144}(e^2 - 1)^{1/2} \left(1 + \frac{673}{602}e^2\right) \right]. \end{aligned}$$

For a parabolic orbit,  $e = 1$ , the radiated energy becomes

$$E = \frac{85\pi}{12\sqrt{2}} \frac{\eta^2 M_{\text{tot}}^{9/2}}{r_p^{7/2}}. \quad (27)$$

**Elliptic orbit  $e < 1$ :** The average of  $P(\phi)$  over one orbital period  $T$  is

$$\begin{aligned} \frac{dE}{dt} &= P = \frac{\omega}{2\pi} \int_0^{2\pi} P(\phi) \frac{dt}{d\phi} d\phi \\ &= \frac{8}{15} \frac{1}{(1-e^2)^{7/2}} \frac{\mu^2 M_{\text{tot}}^3}{a^5} \int_0^{2\pi} \frac{d\phi}{2\pi} (1+e \cos \phi)^2 [e^2 \sin^2 \phi + 12(1+e \cos \phi)^2]. \end{aligned}$$

After performing the integral we arrive at

$$\frac{dE}{dt} = \frac{32}{5} \frac{\mu^2 M_{\text{tot}}^3}{a^5} \frac{1}{(1-e^2)^{7/2}} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right). \quad (28)$$

### 2.2.2 Angular momentum loss

We want to determine the GW-induced angular momentum loss of a binary on a Keplerian orbit. To this end we choose a coordinate system such that the orbits lies in the  $(x, y)$ -plane; then we can set  $L = L_z$ . Therefore

$$\frac{dL}{dt} = \frac{2}{5} \left\langle {}^{(2)}\mathcal{G}_{1a} {}^{(3)}\mathcal{G}_{2a} - {}^{(2)}\mathcal{G}_{2a} {}^{(3)}\mathcal{G}_{1a} \right\rangle.$$

We can integrate the above expression by parts and neglect total derivatives. Even for hyperbolic orbits the total derivatives can be neglected since those terms are the same at  $\pm\infty$ . Therefore we have, again suppressing taking the average at this stage,

$$\frac{dL}{dt} = \frac{4}{5} {}^{(2)}\mathcal{G}_{12} \left( {}^{(3)}\mathcal{G}_{11} - {}^{(3)}\mathcal{G}_{22} \right).$$

The second mass moments in our chosen coordinate frame are given by

$$\mathcal{G}_{a_1 a_2} = \mu r^2 \begin{bmatrix} \cos^2 \phi & \cos \phi \sin \phi & 0 \\ \cos \phi \sin \phi & \sin^2 \phi & 0 \\ 0 & 0 & 0 \end{bmatrix}_{a_1 a_2}. \quad (29)$$

A calculation of the required derivatives gives

$$^{(2)}\mathcal{G}_{12} = \frac{\mu M}{r_p(1+e)} \sin \phi [-4(1+e \cos \phi)^2 \cos \phi + 2e(3 \cos^2 \phi - 1 + 2e \cos^3 \phi)],$$

$$^{(3)}\mathcal{G}_{11} = \left( \frac{4\mu^2 M^3}{[r_p(1+e)]^5} \right)^{1/2} (1+e \cos \phi)^2 (3e \sin \phi \cos^2 \phi + 2 \sin(2\phi)),$$

$$^{(3)}\mathcal{G}_{22} = \left( \frac{4\mu^2 M^3}{[r_p(1+e)]^5} \right)^{1/2} (1+e \cos \phi)^2 (-e(1+3 \cos^2 \phi) \sin \phi - 2 \sin(2\phi)).$$

The angular momentum emitted as a function of  $\phi$  along the orbit is then

$$\frac{dL}{dt} = \frac{8}{5} \frac{\mu^2 M^{5/2}}{[r_p(1+e)]^{7/2}} (1+e \cos \phi)^2 \sin^2 \phi \quad (30)$$

$$\times [-4(1+e \cos \phi)^2 \cos \phi + 2e(3 \cos^2 \phi - 1 + 2e \cos^3 \phi)] \quad (31)$$

$$\times [8 \cos \phi + 6e \cos^2 \phi + e]. \quad (32)$$

**Hyperbolic orbit  $e \geq 1$ :**

$$L = \int_{-\psi}^{\psi} \frac{dL}{dt} \frac{dt}{d\phi} d\phi \quad (33)$$

$$= \frac{8}{5} \frac{\mu^2 M^2}{[r_p(1+e)]^2} \int_{-\psi}^{\psi} d\phi \sin^2(\phi) [8 \cos \phi + 6e \cos^2 \phi + e] \quad (34)$$

$$\times [-4(1+e \cos \phi)^2 \cos \phi + 2e(3 \cos^2 \phi - 1 + 2e \cos^3 \phi)] \quad (35)$$

$$= \frac{8}{5} \frac{\mu^2 M^2}{[r_p(1+e)]^2} \varpi|_{-\psi}^{\psi}, \quad (36)$$

where

$$\begin{aligned} \varpi = & -\frac{7e^2 \phi}{2} - 4\phi - 10e \sin \phi + \frac{5}{16} e^2 \sin(2\phi) + \frac{5}{2} e \sin(3\phi) + \frac{5}{8} e^2 \sin(4\phi) \\ & + \sin(4\phi) + \frac{1}{2} e \sin(5\phi) + \frac{1}{16} e^2 \sin(6\phi). \end{aligned}$$

The evaluation of  $\varpi$  between  $-\psi = -\cos^{-1}(-1/e)$  and  $\psi = \cos^{-1}(-1/e)$  gives

$$\varpi|_{-\psi}^{\psi} = -(7e^2 + 8) \cos^{-1} \left( -\frac{1}{e} \right) \quad (37)$$

$$+ \frac{(e^2 - 1)^{1/2}}{e^4} (-16 + 8e^2 + 12e^4 + 2e^6 - 21e^8). \quad (38)$$

For a parabolic orbit,  $e = 1$ , the emitted angular momentum becomes

$$L = -6\pi \frac{\mu^2 M^2}{r_p^2}. \quad (39)$$

**Elliptic orbit  $e < 1$ :** The angular momentum change averaged over one orbital period is then

$$\frac{dL}{dt} = \frac{\omega}{2\pi} \int_0^{2\pi} \frac{dL}{dt} \frac{dt}{d\phi} d\phi \quad (40)$$

$$= \frac{8}{10\pi} \frac{\mu^2 M^{5/2}}{a^{3/2} [r_p(1+e)]^2} (1-e^2)^{3/2} \varpi|_0^{2\pi}. \quad (41)$$

The expression  $\varpi|_0^{2\pi}$  equals  $-(8+7e^2)$  and we have

$$\frac{dL}{dt} = -\frac{32}{5} \frac{\mu^2 M^{5/2}}{a^{7/2}} \frac{1}{(1-e^2)^2} \left(1 + \frac{7}{8}e^2\right).$$

In case of circular motion, the angular momentum flux is directly proportional to the energy flux:  $\dot{E} = \omega \dot{L}$ .

### 2.2.3 Frequency spectrum

In this section we compute for all  $e \geq 0$  the frequency spectrum of the radiated power. The key ingredient for this is to perform a Fourier decomposition of the binary's second mass moment. The treatise [2] was used as a reference for the theory of Bessel functions.

**Elliptic orbit  $e < 1$ :** We parametrize a elliptic Keplerian orbit in the following form

$$x(\beta) = a(\cos u - e), \quad (42)$$

$$y(\beta) = b \sin u. \quad (43)$$

Here  $a$  is the semi-major axis and  $b$  is the semi-minor axis of the orbit. The eccentric anomaly  $u$  is defined by the Kepler equation

$$u - e \sin u = \omega(t - t_0) \equiv \beta, \quad (44)$$

the time  $t_0$  being an integration constant chosen such that  $x(-\beta) = x(\beta)$  and  $y(\beta) = -y(-\beta)$ . The solution of the Kepler equation can be given as a Fourier expansion involving Bessel functions. To see this we make the Fourier series ansatz

$$y(\beta) \frac{e}{b} = u - \beta = e \sin u = \sum_{n=1}^{\infty} a_n \sin(n\beta), \quad (45)$$

where the coefficients are given by

$$a_m = \frac{2}{\pi} \int_0^{\pi} d\beta (u - \beta) \sin(m\beta). \quad (46)$$



We now compute

$$\begin{aligned}
a_m &= -\frac{2e}{\pi m} \int_0^\pi d\beta \sin u \frac{d}{d\beta} \cos(m\beta) \\
&= \frac{2e}{\pi m} \int_0^\pi du \frac{d \sin u}{du} \cos(mu) \\
&= \frac{2e}{\pi m} \int_0^\pi du \cos u \cos(mu - m \sin u) \\
&= \frac{e}{m} \int_0^\pi \frac{du}{\pi} [\cos(u(m-1) - m \sin u) + \cos(u(m+1) - m \sin u)].
\end{aligned}$$

By using the integral representation of the Bessel functions of the first kind

$$J_n(z) = \int_0^\pi \frac{du}{\pi} \cos(nu - z \sin u) \quad (47)$$

we arrive at

$$a_m = \frac{e}{m} [J_{m-1}(me) + J_{m+1}(me)]. \quad (48)$$

Using the recurrence formula

$$J_{n-1}(z) + J_{n+1}(z) = \frac{2n}{z} J_n(z), \quad (49)$$

this result can be rewritten as

$$a_m = \frac{2}{m} J_m(me). \quad (50)$$

Similarly we write  $\frac{x(\beta)}{a} = \cos u - e = b_0 + \sum_{n=1}^\infty b_n \cos(n\beta)$  and find for the corresponding expansion coefficients

$$b_0 = -\frac{3}{2}e, \quad (51)$$

$$b_m = \frac{1}{m} [J_{m-1}(z) - J_{m+1}(z)] = \frac{2}{m} J'_m(me); \quad (52)$$

the prime denotes the derivative with respect to its argument. Next we compute the Fourier expansion of  $x^2(\beta)$ ,  $y^2(\beta)$  and  $x(\beta)y(\beta)$ . We can again write

$$y^2(\beta) = A_0 + \sum_{n=1}^\infty A_n \cos(n\beta), \quad (53)$$

$$x^2(\beta) = B_0 + \sum_{n=1}^\infty B_n \cos(n\beta), \quad (54)$$

$$y(\beta)x(\beta) = \sum_{n=1}^\infty C_n \sin(n\beta), \quad (55)$$

together with

$$A_m = \frac{2}{\pi} \int_0^\pi d\beta y^2(\beta) \cos(m\beta), \quad (56)$$

$$B_m = \frac{2}{\pi} \int_0^\pi d\beta x^2(\beta) \cos(m\beta), \quad (57)$$

$$C_m = \frac{2}{\pi} \int_0^\pi d\beta x(\beta)y(\beta) \sin(m\beta). \quad (58)$$

Similar to the calculation of  $a_n$  we obtain

$$A_m = \frac{b^2}{m} [J_{m+2}(me) - J_{m-2}(me)], \quad (59)$$

$$B_m = \frac{a^2}{m} [J_{m-2}(me) - J_{m+2}(me) - 4eJ'_m(me)], \quad (60)$$

$$C_m = \frac{ba}{m} [J_{m+2}(me) + J_{m-2}(me) - 2J_m(me)], \quad (61)$$

along with  $A_0 = \frac{1}{2}$  and  $B_0 = \frac{1+4e^2}{2}$ .

Likewise we expand the second mass moment (15) as

$$\mathcal{G}_{a_1 a_2} = \mu \sum_{n=0}^{\infty} \begin{bmatrix} B_n \cos(n\beta) & C_n \sin(n\beta) & 0 \\ C_n \sin(n\beta) & A_n \cos(n\beta) & 0 \\ 0 & 0 & 0 \end{bmatrix}_{a_1 a_2} \equiv \sum_{n=0}^{\infty} \mathcal{G}_{a_1 a_2}^{(n)}. \quad (62)$$

The emitted power in the quadrupole approximation is obtained from the formulae (13) and (23)

$$P = \frac{8\pi}{75} \sum_{m=-2}^2 \left\langle \left| {}^{(3)}\mathcal{G}_{a_1 a_2} (\mathcal{Y}_{a_1 a_2}^{2m})^* \right|^2 \right\rangle. \quad (63)$$

Since  $\langle \cos(n\beta) \cos(m\beta) \rangle = \langle \sin(n\beta) \sin(m\beta) \rangle = \frac{1}{2} \delta_{mn}$ , different harmonics don't contribute in the power spectrum. Hence we can set  $P = \sum_{n=1}^{\infty} P_n$ , where the power radiated in the  $n$ -th harmonics is

$$P_n = \frac{8\pi}{75} \sum_{m=-2}^2 \left\langle \left| {}^{(3)}\mathcal{G}_{a_1 a_2}^{(n)} (\mathcal{Y}_{a_1 a_2}^{2m})^* \right|^2 \right\rangle, \quad (64)$$

together with

$${}^{(3)}\mathcal{G}_{a_1 a_2}^{(n)} = \mu(\omega n)^3 \begin{bmatrix} B_n \sin(n\beta) & -C_n \cos(n\beta) & 0 \\ -C_n \cos(n\beta) & A_n \sin(n\beta) & 0 \\ 0 & 0 & 0 \end{bmatrix}_{a_1 a_2}. \quad (65)$$

The explicit form of the STF tensors  $\mathcal{Y}_{a_1 a_2}^{2m}$  is given by

$$\mathcal{Y}_{a_1 a_2}^{22} = \left( \frac{15}{32\pi} \right)^{1/2} \begin{pmatrix} 1 & i & 0 \\ i & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}_{a_1 a_2}, \quad (66)$$

$$\mathcal{Y}_{a_1 a_2}^{21} = - \left( \frac{15}{32\pi} \right)^{1/2} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & i \\ 1 & i & 0 \end{pmatrix}_{a_1 a_2}, \quad (67)$$

$$\mathcal{Y}_{a_1 a_2}^{20} = \left( \frac{5}{16\pi} \right)^{1/2} \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 2 \end{pmatrix}_{a_1 a_2}, \quad (68)$$

together with  $\mathcal{Y}_{a_1 a_2}^{2-m} = (-1)^m (\mathcal{Y}_{a_1 a_2}^{2m})^*$ . The power in the  $n$ -th harmonic can now be determined and a calculations gives

$$P_n = \frac{1}{15} \mu^2 (\omega n)^6 (A_n^2 + B_n^2 + 3C_n^2 - A_n B_n). \quad (69)$$

**Hyperbolic orbit  $e \geq 1$ :** We parametrize the coordinates on an hyperbolic orbit as

$$x(\beta) = a(e - \cosh u), \quad (70)$$

$$y(\beta) = b \sinh u, \quad (71)$$

where  $u$  satisfies the hyperbolic Kepler equation

$$e \sinh(u) - u = \Omega t \equiv \beta. \quad (72)$$

The second mass moment (15) has the form

$$\begin{aligned} \mathcal{G}_{a_1 a_2} &= \mu \begin{bmatrix} a^2(e - \cosh u)^2 & ab(e - \cosh u) \sinh u & 0 \\ ab(e - \cosh u) \sinh u & b^2 \sinh^2 u & 0 \\ 0 & 0 & 0 \end{bmatrix}_{a_1 a_2} \\ &= \mu \begin{bmatrix} a^2(e^2 - 2e \cosh u + \frac{1}{2} \cosh(2u) + \frac{1}{2}) & ab(e \sinh u - \frac{1}{2} \sinh(2u)) & 0 \\ ab(e \sinh u - \frac{1}{2} \sinh(2u)) & \frac{b^2}{2} \cosh(2u) - \frac{b^2}{2} & 0 \\ 0 & 0 & 0 \end{bmatrix}_{a_1 a_2}. \end{aligned} \quad (73)$$

The total radiated energy has the form

$$E = \frac{8\pi}{75} \int_{-\infty}^{\infty} dt \sum_{m=-2}^2 \left| {}^{(3)}\mathcal{G}_{a_1 a_2} (\mathcal{Y}_{a_1 a_2}^{2m})^* \right|^2 \quad (75)$$

$$= \frac{1}{2\pi} \frac{8\pi}{75} \int_{-\infty}^{\infty} d\omega \sum_{m=-2}^2 \left| \widehat{[{}^{(3)}\mathcal{G}_{a_1 a_2} (\mathcal{Y}_{a_1 a_2}^{2m})^*]} \right|^2 \quad (76)$$

$$\equiv \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega P(\omega). \quad (77)$$

where the second equality follows from Plancherel's theorem and the hat represents the Fourier transform. We can take the derivative

$$P(\omega) = \frac{8\pi}{75} \omega^6 \sum_{m=-2}^2 \left| (\mathcal{Y}_{a_1 a_2}^{2m})^* \widehat{\mathcal{G}_{a_1 a_2}} \right|^2, \quad (78)$$

and it remains to calculate the Fourier transform of  $\mathcal{G}_{a_1 a_2}$

$$\begin{aligned} \widehat{\mathcal{G}_{a_1 a_2}} &= \int_{-\infty}^{\infty} du \frac{dt(u)}{du} e^{-i\omega t(u)} \mathcal{G}_{a_1 a_2} \\ &= -\frac{1}{i\omega} \int_{-\infty}^{\infty} du \frac{d}{du} \left( e^{-i\omega t(u)} \right) \mathcal{G}_{a_1 a_2}. \end{aligned}$$

We will continue the calculation for the  $\sinh(nu)$  terms

$$\begin{aligned} \widehat{\sinh(nu)} &= -\frac{1}{i\omega} \int_{-\infty}^{\infty} du \frac{d}{du} \left( e^{-i\omega t(u)} \right) \sinh(nu) \\ &= \frac{n}{i\omega} \int_{-\infty}^{\infty} du e^{-i\omega t(u)} \cosh(nu) \\ &= \frac{n}{2i\omega} \int_{-\infty}^{\infty} du e^{-i\frac{\omega}{\Omega}(e \sinh u - u)} (e^{nu} + e^{-nu}) \\ &= \frac{n}{2i\omega} \int_{-\infty}^{\infty} du \left( e^{-i\frac{\omega}{\Omega} e \sinh u + (i\frac{\omega}{\Omega} + n)u} + e^{-i\frac{\omega}{\Omega} e \sinh u + (i\frac{\omega}{\Omega} - n)u} \right). \end{aligned}$$

This result can be expressed in terms of modified Bessel functions of the second kind  $K_\nu(x)$ . One possible integral representation of  $K_\nu(x)$  has the form

$$K_\nu(x) = \frac{1}{2} e^{\frac{1}{2}\nu\pi i} \int_{-\infty}^{\infty} dt e^{-ix \sinh t + \nu t}. \quad (79)$$

With this we can write

$$\widehat{\sinh(nu)} = \frac{n}{i\omega} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} e^{-\frac{1}{2}n\pi i} \left[ K_{i\frac{\omega}{\Omega}+n} \left( \frac{\omega}{\Omega} e \right) + e^{i\pi n} K_{i\frac{\omega}{\Omega}-n} \left( \frac{\omega}{\Omega} e \right) \right]. \quad (80)$$

For the relevant terms for  $\widehat{\mathcal{G}_{a_1 a_2}}$  we get

$$\widehat{\sinh(u)} = -\frac{1}{\omega} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} \left[ K_{i\frac{\omega}{\Omega}+1} \left( \frac{\omega}{\Omega} e \right) - K_{i\frac{\omega}{\Omega}-1} \left( \frac{\omega}{\Omega} e \right) \right], \quad (81)$$

$$\widehat{\sinh(2u)} = -\frac{2}{i\omega} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} \left[ K_{i\frac{\omega}{\Omega}+2} \left( \frac{\omega}{\Omega} e \right) + K_{i\frac{\omega}{\Omega}-2} \left( \frac{\omega}{\Omega} e \right) \right]. \quad (82)$$

The calculation of  $\widehat{\cosh(nu)}$  proceeds the same way and one finds

$$\widehat{\cosh(nu)} = \frac{n}{i\omega} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} e^{-\frac{1}{2}n\pi i} \left[ K_{i\frac{\omega}{\Omega}+n} \left( \frac{\omega}{\Omega} e \right) - e^{i\pi n} K_{i\frac{\omega}{\Omega}-n} \left( \frac{\omega}{\Omega} e \right) \right], \quad (83)$$

so that

$$\widehat{\cosh(u)} = -\frac{1}{\omega} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} \left[ K_{i\frac{\omega}{\Omega}+1} \left( \frac{\omega}{\Omega} e \right) + K_{i\frac{\omega}{\Omega}-1} \left( \frac{\omega}{\Omega} e \right) \right], \quad (84)$$

$$\widehat{\cosh(2u)} = -\frac{2}{i\omega} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} \left[ K_{i\frac{\omega}{\Omega}+2} \left( \frac{\omega}{\Omega} e \right) - K_{i\frac{\omega}{\Omega}-2} \left( \frac{\omega}{\Omega} e \right) \right]. \quad (85)$$

We can now use the recurrence relations

$$K_\nu(x) = -\frac{x}{2\nu} [K_{\nu-1}(x) - K_{\nu+1}(x)], \quad (86)$$

$$K'_\nu(x) = -\frac{1}{2} [K_{\nu-1}(x) + K_{\nu+1}(x)], \quad (87)$$

to derive the following identities

$$K_{\nu+2}(x) + K_{\nu-2}(x) = \left( \frac{4\nu^2}{x^2} + 2 \right) K_\nu(x) - \frac{4}{x} K'_\nu(x), \quad (88)$$

$$K_{\nu+2}(x) - K_{\nu-2}(x) = -\frac{4\nu}{x} K'_\nu(x) + \frac{4\nu}{x^2} K_\nu(x). \quad (89)$$

Combining the above we arrive at

$$\widehat{\sinh(u)} = -\frac{2i}{\omega e} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} K_{i\frac{\omega}{\Omega}} \left( \frac{\omega}{\Omega} e \right), \quad (90)$$

$$\widehat{\sinh(2u)} = -\frac{2}{i\omega} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} \left[ \left( \frac{-4}{e^2} + 2 \right) K_{i\frac{\omega}{\Omega}} \left( \frac{\omega}{\Omega} e \right) - \frac{4}{\frac{\omega}{\Omega} e} K'_{i\frac{\omega}{\Omega}} \left( \frac{\omega}{\Omega} e \right) \right], \quad (91)$$

$$\widehat{\cosh(u)} = \frac{2}{\omega} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} K'_{i\frac{\omega}{\Omega}} \left( \frac{\omega}{\Omega} e \right), \quad (92)$$

$$\widehat{\cosh(2u)} = \frac{8}{e\omega} e^{\frac{1}{2}\frac{\omega}{\Omega}\pi} \left[ K'_{i\frac{\omega}{\Omega}} \left( \frac{\omega}{\Omega} e \right) - \frac{1}{\frac{\omega}{\Omega} e} K_{i\frac{\omega}{\Omega}} \left( \frac{\omega}{\Omega} e \right) \right]. \quad (93)$$

To write down a final formula for the gravitational wave energy spectrum of an hyperbolic encounter, one merely needs to insert the above identities into equation (78). However, we refrain from writing down this expression, since there seems little hope to simplify the tediously long expressions.

### 3 Formation of binaries through gravitational wave capture

When two black holes on a parabolic trajectory have a near encounter, they may release sufficiently energy through gravitational waves to form a bound binary. In the center of mass system, the initial energy of two non-interacting black holes is  $E_{\text{ini}} = \frac{\mu v^2}{2}$  while the angular momentum of the system reads  $L_{\text{ini}} = \mu v b$ . Conservation of energy and angular momentum of the system before and after the encounter gives

$$E_{\text{fin}} = \frac{\mu v^2}{2} - \frac{85\pi}{12\sqrt{2}} \frac{\eta^2 M^{9/2}}{r_p^{7/2}}, \quad (94)$$

$$L_{\text{fin}} = \mu v b - 6\pi \frac{\mu^2 M^2}{r_p^2}, \quad (95)$$

where the rightmost terms are the released energy through gravitational waves during a parabolic encounter and the amount of angular momentum lost during a parabolic encounter respectively. For there to form a bound binary system, the final energy  $E_{\text{fin}}$  must be negative. This criterion gives a constraint for the formation of a bound binary. Accordingly, the maximal impact parameter of two colliding BHs with relative velocity  $v$  to form a binary is

$$b_{\text{max}} = M \left( \frac{340\pi}{3} \right)^{1/7} \left( \frac{\eta}{v^9} \right)^{1/7}, \quad (96)$$

where we used equation (3), the pericenter distance  $r_p$  expanded to first order in the relative velocity  $v$ . The orbital semi-major axis after the encounter is

$$a_0 = \frac{\mu M}{2|E_{\text{fin}}|}, \quad (97)$$

while the orbital eccentricity after the encounter reads

$$e_0^2 - 1 = \frac{2E_{\text{fin}}L_{\text{fin}}^2}{M^2\mu^3} = \frac{2E_{\text{fin}}v^2b^2}{M^2\mu}, \quad (98)$$

where we neglected the angular momentum loss due to gravitational wave emission (performed population simulations and found that for almost all encounters  $L_{\text{fin}} \approx \mu v b$ ). Substituting  $b_{\text{max}}$  in equation (3) the corresponding maximum pericenter distance reads

$$r_{p,\text{max}} = 2^{-3/7} M_{\text{tot}} \left( \frac{85\pi}{3} \right)^{2/7} v^2 \left( \frac{t}{v^9} \right)^{2/7} \left[ 1 - 2^{-10/7} \left( \frac{85\pi}{3} \right)^{2/7} v^4 \left( \frac{t}{v^9} \right)^{2/7} \right] \quad (99)$$

### 4 Dynamics affecting the binary's orbital evolution

The hardening time  $\frac{a}{\dot{a}}$  is the time a binary spends at each semimajor-axis  $a$ .

#### 4.1 GW-driven inspiral of binary

Once a binary is formed its orbital parameters are affected due to the release of gravitational waves.

Substituting the energy loss equation (28) into the evolution equation (8) one finds the GW driven evolution of the semi-major axis

$$\frac{da}{dt} = -\frac{64}{5} \frac{\mu M_{\text{tot}}^2}{a^3} \frac{1}{(1-e^2)^{7/2}} \left( 1 + \frac{73}{24}e^2 + \frac{37}{96}e^4 \right). \quad (100)$$

Substituting both (28) and (42) into the evolution equation (10) one finds the GW driven evolution of the orbit eccentricity

$$\frac{de}{dt} = -\frac{304}{15} \frac{\mu M_{\text{tot}}^2}{a^4} \frac{e}{(1-e^2)^{5/2}} \left( 1 + \frac{121}{304}e^2 \right). \quad (101)$$

Combining equations (100) and (101) gives

$$\frac{da}{de} = \frac{12}{19} a \frac{1 + (73/24)e^2 + (37/96)e^4}{e(1-e^2) \left( 1 + e^2 \frac{121}{304} \right)}. \quad (102)$$

The solution of the differential equation (102) is

$$a(e) = c_0 \frac{e^{12/19}}{1-e^2} \left( 1 + \frac{121}{304}e^2 \right)^{870/2299}, \quad (103)$$

where  $c_0$  depends on the initial semi-major axis  $a_0$  and the initial orbital eccentricity  $e_0$ . By requiring  $a(e_0) = a_0$  we can set

$$c_0 = a_0 (1-e_0^2) e_0^{-12/19} \left( 1 + \frac{121}{304}e_0^2 \right)^{-\frac{870}{2299}}.$$

From the orbit equation (1) we find that the orbital frequency is related to the eccentricity by

$$\frac{\omega}{\omega_0} = \left[ \left( \frac{e}{e_0} \right)^{\frac{12}{19}} \frac{1-e_0^2}{1-e^2} \left( \frac{1 + \frac{121}{304}e^2}{1 + \frac{121}{304}e_0^2} \right)^{\frac{870}{2299}} \right]^{-3/2}, \quad (104)$$

with the initial orbital frequency  $\omega_0 = \sqrt{\frac{M}{a_0^3}}$ .

To find the time to coalescence  $\tau$  we can integrate the inverse to equation (101) by requiring that  $e(\tau) = 0$  (at coalescence the eccentricity  $e$  goes to zero). The lifetime is thus given by the integral

$$\tau = \frac{15}{304} \frac{1}{\mu M_{\text{tot}}^2} \int_0^{e_0} de a^4 \frac{(1-e^2)^{5/2}}{e} \left( 1 + \frac{121}{304}e^2 \right)^{-1}. \quad (105)$$

We now simplify this expression for an initial parabolic orbit. We write the last equation using equation (103) and note that the integral is dominated by  $e$  near

1, thus giving

$$\tau = a_0^4 \frac{15}{304} \frac{1}{\mu M_{\text{tot}}^2} (1 - e_0^2)^4 \int_0^{e_0} de \frac{(1 - e^2)^{5/2}}{(1 - e^2)^4} \left(1 + \frac{121}{304}\right)^{-1} \quad (106)$$

$$= a_0^4 \frac{15}{425} \frac{1}{\mu M_{\text{tot}}^2} (1 - e_0^2)^4 \int_0^{e_0} de (1 - e^2)^{-3/2} \quad (107)$$

$$\approx a_0^4 \frac{15}{425} \frac{1}{\mu M_{\text{tot}}^2} \frac{(1 - e_0^2)^4}{(1 - e_0^2)^{1/2}} = a_0^4 \frac{3}{85} \frac{1}{\mu M_{\text{tot}}^2} (1 - e_0^2)^{7/2}. \quad (108)$$

As initial semi-major axis  $a_0$  and initial eccentricity  $e_0$  for the bound binary we use the expressions (4) and (6). The time to merger is thus

$$\tau = \left(\frac{\eta M_{\text{tot}}^2}{2E_{\text{fin}}}\right)^4 \frac{3}{85} \frac{1}{\mu M_{\text{tot}}^2} \left(\frac{2E_{\text{fin}} v^2 b^2}{M_{\text{tot}}^2 \mu}\right)^{7/2} \quad (109)$$

$$= \frac{3\sqrt{2}}{170} \frac{1}{E_{\text{fin}}^{1/2} M_{\text{tot}}} \frac{\eta^4}{\mu^{9/2}} v^7 b^7. \quad (110)$$

As the merger time depends on  $v$  to the seventh power, we can ignore the contribution of the kinetic part of the final energy  $E_{\text{fin}}$  and thus use for  $E_{\text{fin}}$  the expression (27). In this approximation, and upon expressing  $r_p$  in  $\delta E$  with its parametrized form (3), the merger time reads

$$\tau = \frac{3}{170} \sqrt{\frac{3}{85\pi}} \frac{(bv)^{21/2}}{\eta^{3/2} M_{\text{tot}}^{19/2}}. \quad (111)$$

## 4.2 Disk - BBH dynamics

The interaction between the binary system and the gaseous disk in which it is embedded is complicated and several mechanisms are at play.

At some point, the tidal torques exerted by the binary onto the disc are sufficiently high to repel gas away from the binary, thus clearing a cavity around the binary. Furthermore, the binary may then be surrounded by a circumbinary disc which affects the orbital evolution of the central binary. The disc-binary interaction drives the binary ultimately into the phase of GWs-driven inspiral, where loss of orbital energy and angular momentum is due to the emission of gravitational waves.

### 4.2.1 (Simplified) model of AGN

The equation for hydrostatic equilibrium in the vertical direction for a geometrically thin disk in a central gravitational potential is

$$\frac{dp}{dz} = -\rho \frac{Mz}{r^3}, \quad (112)$$

where  $p(r, z)$  and  $\rho(r, z)$  are the pressure and mass density at radius  $r$  and height  $z$ . We assume the disk to be isothermal in the vertical direction, yielding  $c_s^2 = \frac{p}{\rho}$ , where  $c_s$  is the sound speed (independent of  $z$ ). Then we obtain for the mass density

$$\rho = \rho_0 e^{-\frac{z^2}{2h^2}}, \quad (113)$$

with the density at the equatorial plane  $\rho_0$  and with the disk scale height

$$h = \frac{c_s r^{3/2}}{M^{1/2}} = \frac{c_s}{\Omega}. \quad (114)$$

The total mass enclosed within a radius  $r$  is denoted by  $M(r)$  and is related to the surface density  $\Sigma(r)$  through  $\frac{dM(r)}{dr} = 2\pi r \Sigma(r)$ . In the AGN model outlined in [3], the disk mass  $M(r)$  is set to  $2\sigma^2 r$ , where  $\sigma$  stands for the velocity dispersion of the gas. The associated surface density is then

$$\Sigma(r) = \frac{\sigma^2}{\pi r}. \quad (115)$$

Furthermore, the following relations are imposed to the disk data

$$\frac{f_g}{2^{3/2}} = \frac{h}{r} = \frac{1}{\sqrt{2}} \frac{c_s}{\sigma}, \quad (116)$$

where  $f_g = \frac{\Sigma}{\Sigma_g}$  is the total surface density  $\Sigma$  divided by the gas surface density  $\Sigma_g$ . The last relation ensures that ...

#### 4.2.2 A little on accretion disks

**Continuity equation for accretion disks** Suppose that a gaseous disk has surface density  $\Sigma(r)$  and radial velocity  $v_\phi = r\Omega(r) = \frac{\dot{M}}{r}$ . The structure and the evolution of gaseous disks can be deduced from the continuity equation

$$2\pi r \frac{\partial \Sigma}{\partial t} = \frac{\partial \dot{M}}{\partial r}, \quad (117)$$

and from angular momentum conservation

$$\frac{\partial(\Omega r^2)}{\partial r} \dot{M} = \frac{\partial}{\partial r}(T_{\text{visc}}). \quad (118)$$

Combining equations (117) and (118) gives an evolution equation for the surface density  $\Sigma$ ,

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{2\pi r} \frac{\partial}{\partial r} \left[ \left( \frac{\partial(\Omega r^2)}{\partial r} \right)^{-1} \frac{\partial(T_{\text{visc}})}{\partial r} \right]. \quad (119)$$

We can incorporate external effects interacting with the disk into the viscous evolution equation of the disk. If the disk experiences an external torque per unit mass  $\tilde{T}_{\text{ext}}$ , we modify the surface density evolution in the following form

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{2\pi r} \frac{\partial}{\partial r} \left[ \left( \frac{\partial(\Omega r^2)}{\partial r} \right)^{-1} \frac{\partial(T_{\text{visc}})}{\partial r} + \frac{4\pi \Sigma \tilde{T}_{\text{ext}}}{\Omega} \right] \quad (120)$$

$$= \frac{1}{2\pi r} \frac{\partial}{\partial r} \left[ \left( \frac{\partial(\Omega r^2)}{\partial r} \right)^{-1} \frac{\partial(T_{\text{visc}} + T_{\text{ext}})}{\partial r} \right], \quad (121)$$

defining  $\frac{\partial T_{\text{ext}}}{\partial r} = 8\pi \Sigma \tilde{T}_{\text{ext}} r$ .



**Viscous Torque in the Disc** Because the angular velocity of the accretion disk varies with radius, a viscous torque is acting on the gas. This torque represents the amount of angular momentum crossing the disk circumference at radius  $r$  per unit time due to the action of viscosity. The shear stress is  $\tau = \rho(r)\nu r \frac{d\Omega}{dr}$ , where  $\nu$  is the dynamical viscosity and  $\rho(r)$  the mass density. This leads to a viscous torque between two neighbouring disk annuli at radius  $r$

$$T_{\text{visc}} = 2\pi r \int dz r \tau = 2\pi \nu \Sigma(r) r^3 \frac{d\Omega}{dr}, \quad (122)$$

where  $\Sigma(r) = \int dz \rho(r)$  is the surface density of the disk. By employing the Keplerian orbital frequency it follows that the torque is

$$T_{\text{visc}} = -3\pi \nu \Sigma(r) r^2 \Omega(r). \quad (123)$$

One may employ the  $\alpha$ -disk prescription to parametrize the dynamical viscosity in the case for a thin accretion disk as  $\nu = \alpha c_s^2(r) \Omega(r)^{-1}$ , where  $c_s(r)$  is the local gas sound speed and  $0 \leq \alpha \leq 1$  is a dimensionless constant. Substituting this value for  $\nu$  into the expression for  $T_{\text{visc}}$  gives

$$T_{\text{visc}} = -3\pi \alpha c_s^2(r) \Sigma(r) r^2. \quad (124)$$

Note that this torque is negative, resulting in an outward transfer of angular momentum.

#### 4.2.3 Evolution of binary in global disk

Several simulations suggest that a binary system carves an annular gap or even a cavity into the global disk. The presence of such a gap may help to both understand how the binary migrates towards the central disk mass and how its orbital parameters evolve.

**Criterion for gap-opening in disk** In order for the binary to open a gap in the disk, the gap-opening torque must be greater than the gap-closing torque. Crida et al. [4] derived a semi-analytical criterion for gap-opening based on the balance between pressure, gravitational and viscous torques for a compact object on a fixed circular orbit around a central mass  $M_*$ . Adapting their work to binary systems orbiting circularly around a central mass may not be justified. The parameters of the binary orbit are expected to complicate the mechanisms of gap-opening. However, deriving a formula which additionally takes into account the internal angular momentum of the binary, its semi-major-axis and its eccentricity seems without resorting to numerical simulations out of reach. Such simulations have been performed and are discussed in section (4.2.4) and suggest that the simplified criterion for gap-opening may nevertheless be useful. The gap-opening criterion is given by  $g \lesssim 1$ , where

$$g = \frac{3}{4} \frac{h}{R_{\text{Hill}}} + \frac{50\nu_b}{qr_b^2\Omega_b}. \quad (125)$$

Here  $r_b$  is the distance from the center of mass of the binary to the central mass  $M_*$ ,  $h$  denotes the thickness of the disk,  $R_{\text{Hill}} = r_b \left( \frac{M_b}{3M_*} \right)^{1/3}$  is the Hill radius of

the binary,  $\Omega_b = \sqrt{\frac{M_b + M_*}{r_b^3}}$  is the angular orbital frequency of the binary-central mass system and  $\nu_b$  is the dynamical viscosity of the disk at the binary orbit. Writing the disk viscosity according to the  $\alpha$ -disk model, the inequality becomes

$$g = \frac{3}{4} \frac{h}{R_{\text{Hill}}} + \frac{50\alpha h^2 \Omega_r}{q r_b^2 \Omega_b}, \quad (126)$$

where again  $h = c_s / \Omega_r = c_s \sqrt{\frac{r^3}{M_*}}$  is the scale height of the disk.

For  $\alpha = 0.01$  and a disk scale height varying from  $10^{-3}$  at 0.01pc to  $10^{-2}$  at 1pc, table (1) lists some approximate disc radii in parsec up to which a gap may be opened (horizontal: Central mass  $M_*$  in solar masses, vertical: Binary mass  $M_b$  in solar masses)

	$3 \times 10^5$	$3 \times 10^6$	$3 \times 10^7$
10	1.75	0.06	$\ll 0.01$
20	4.71	0.17	$< 0.01$
30	8.38	0.31	0.01
40	$> 10$	0.47	0.02
50	$> 10$	0.63	0.02
100	$> 10$	1.74	0.06
150	$> 10$	3.16	0.11
200	$> 10$	4.68	0.17

Table 1: Approximate disk radii in parsec up to which a binary system may open a gap in its embedded disk.

#### 4.2.4 Internal orbital evolution

Numerical simulations suggest the presence of a depleted cavity inside of which the binary resides (Condition: the binary mass ratio  $q$  gets closer to unity). The gas orbiting around this cavity is referred to as the circumbinary disk (CBD). The evolution of the semi-major axis and of the orbital eccentricity are driven by tidal and viscous interaction between the binary and the CBD. As we will see this results in a loss of the binary's orbital angular momentum, a increase in its eccentricity and its faster inspiral.

We thus now assume that a central cavity is surrounded by a CBD. For simplicity we assume that neither the primary nor the secondary have their own disks. We aim to relate the viscous angular momentum flux in the inner region of the disk to the orbital evolution of the binary.

When the disk absorbs angular momentum from the binary , the radial inflow of gas should slow down and it would accumulate in the inner disk, compared to the constant- solution. The amount of mass pileup is determine. (could habe opposite sign, but that is not wha simulations suggest, difficult to accommodate with simulations)

Numerical simulations suggest that the size of the central cavity extends to about twice the semi-major axis of the binary orbit (as seen from the center of mass frame). The majority of those simulations, however, assume circular

orbits or such with low values for  $e$ . Nevertheless, has confirmed that this value is also applicable for a binary black hole with a moderate eccentricity of  $e = 0.5$ . Inspired by their findings, we thus assume that the inner edge of the circumbinary disk is set by the twice the semi-major axis *i.e.*  $r_{\text{in}} = 2a$  and extrapolate the estimates of the radius of the circular inner edge also to eccentricities higher than  $e = 0.5$ . Tidal torques from the binary are expected to act significantly only on a narrow annulus at the inner edge of the CBD and are thus assumed to be zero outside of some cutoff radius  $r_{\Lambda}$ , which is very similar to  $r_{\text{in}}$ . Thus the effect of the binary torque on the disk evolution can be accounted for via equation (121) by imposing suitable boundary conditions at the inner edge of the disk. From equation (121) we can thus deduce

$$\left(\frac{\partial(\Omega r^2)}{\partial r}\right) \dot{M} = \frac{\partial(T_{\text{visc}})}{\partial r} + \left(\frac{\partial(\Omega r^2)}{\partial r}\right) \frac{4\pi\Sigma\tilde{T}_{\text{ext}}}{\Omega}. \quad (127)$$

Integrating from  $r_b$  to  $r_{\Lambda}$  we obtain (check this at some point)

$$T_{\text{visc}}(r_{\Lambda}) = 8\pi \int_{r_b}^{r_{\Lambda}} dr r \Sigma \tilde{T}_{\text{ext}} - 2 \int_{r_b}^{r_{\Lambda}} dr r \Omega \dot{M}; \quad (128)$$

we have set  $T_{\text{visc}}(r_b) = 0$  because of the clean gap assumption.

The first integral on the right hand side is the total torque the binary exerts on the disk. It is the rate of the angular momentum injection into the disk by the binary. As long as the evolution of the binary is driven predominantly by the tidal coupling to the disk (and not due to the gravitational wave emission) conservation of angular momentum guarantees that this term equals  $-\dot{J}_b$ , the change of angular momentum of the binary. In the right integral on the right side we can write

$$\dot{M} = 2\pi\Sigma r v_r = 3\pi\Sigma\nu = 3\pi\Sigma\alpha c_s^2/\Omega. \quad (129)$$

Because of the clean gap assumption, the disk surface density  $\Sigma$  is zero for  $r < r_{\text{in}}$ . Then we approximate the integral by

$$\begin{aligned} \Delta &\equiv -6\pi\alpha c_s^2\Sigma(r_{\text{in}}) \int_{r_{\text{in}}}^{r_{\Lambda}} dr r \\ &= -3\pi\alpha c_s^2\Sigma(r_{\text{in}}) [r_{\Lambda}^2 - r_{\text{in}}^2] \\ &\approx -3\pi\alpha c_s^2\Sigma(r_{\text{in}})\delta r_{\text{in}}, \end{aligned}$$

where the disk density in the small radial annulus  $[r_{\text{in}}, r_{\Lambda}]$  around the cavity edge we set to  $\Sigma(r_{\text{in}})$  since  $r_{\Lambda} - r_{\text{in}} = \delta/2 \ll r_{\text{in}}$  and since we have no model to resolve the surface density of the CBD down to this scale.

Therefore we may suppose that  $T_{\text{visc}}(r_{\text{in}}) = -\dot{J}_b - \Delta$ . Recall that  $r_{\text{in}} = 2a$ , so the viscous torque (124) reads  $T_{\text{visc}}(2a) = 12\pi\alpha c_s^2\Sigma(2a)a^2$ . As this term is a few order of magnitudes higher than  $\Delta$ , we may neglect  $\Delta$  henceforth.

The criterion for applicability of the relation between the orbital averaged energy and angular momentum is that the evolution of the binary energy and the binary angular momentum may well be approximated as an adiabatic process

(as opposed to a evolution driven by sudden perturbations). A perturbation is weak enough to induce adiabatic changes if the energy of the perturbation is much lower than some characteristic frequency of the system. For a binary system we may for example argue that the characteristic timescale of the perturbation should be much larger than the orbital period. How can we define or characterize the timescale of the disk-binary interaction? Does it meet the adiabatic criterion? Timescale of increase/decrease of ?? by disk-binary interaction: 7 Timescale of for a system to merge by  
- or: We impose this condition!! By construction then it is an adiabatic process! Not adiabatic if e.g.  $dE$  during one period is  $\approx$  escape energy.  
Gravitational: Timescale for coalescence via emission of gravitational radiation. Tune it such that it does satisfy adiabatic approximation. Timescale of outward viscous angular momentum transport in the disk? By construction, the timescale of the secondary is of order the viscous timescale at  $r_i n$ . Is  $a/\dot{a}$  - but how estimate it before knowing result, before using the imposed condition? Disk-binary interaction increases orbital frequency on a characteristic scale, definition,  $\omega/\omega_{\text{disk}}$ .

We assume that the disk material at the inner disk edge has an orbital frequency equal to the angular frequency of the binary system, the binary and the disk are then said to corotate. Then the change in the binary energy is related to its change in angular momentum through the orbital frequency,  $\dot{E}_b = \Omega_b \dot{J}_b$ . In general, and as we will see in XX, if the orbital frequency of the binary and the disk do not coincide, other resonances appear. Note that  $\dot{J}_b < 0$ , so  $\dot{E}_b < 0$  and therefore the binary always evolves toward lower energy. In particular the initially bound orbit always stays on an elliptic orbit. Energy conservation implies that energy is deposited in the circumbinary disk. From the evolution equation (8) for the semi-major axis of the binary orbit and the binary energy  $E_b = -\frac{\Omega_b J_b}{2\sqrt{1-e^2}}$  it follows therefore

$$\frac{\dot{a}}{a} = -\frac{\dot{E}_b}{E_b} = -\frac{T_{\text{visc}}(r_{\text{in}})}{J_b} 2\sqrt{1-e^2} \quad (130)$$

$$= -2\frac{T_{\text{visc}}(r_{\text{in}})}{\mu\Omega_b a^2}, \quad (131)$$

where the last equation follows by substituting the orbital angular momentum (5). Substituting the explicit formula for the viscous torque results in

$$\frac{\dot{a}}{a} = -\frac{24\pi\alpha c_s^2 \Sigma(2a)}{\mu\Omega_b}. \quad (132)$$

Similarly we obtain for the evolution of the eccentricity

$$\frac{e\dot{e}}{1-e^2} = \left(\frac{1}{\sqrt{1-e^2}} - 1\right) \frac{T_{\text{visc}}(r_{\text{in}})}{\mu\Omega_b a^2} \quad (133)$$

$$= \left(\frac{1}{\sqrt{1-e^2}} - 1\right) \frac{12\pi\alpha c_s^2 \Sigma(2a)}{\mu\Omega_b}. \quad (134)$$

We see that while the semi-major axis decreases, the orbital eccentricity increases. Recall that although  $\dot{e} > 0$ , the orbit cannot become unbound since the

orbit's energy decreases.

What values of  $\alpha, \Sigma$  and  $c_s$  of the CBD should be used? Baruteau et al. [5] use the same values as those of the global AGN disk. It is argued that the quantities taken at the inner edge of the CBD should not differ significantly from the quantities taken at the outer edge of the CBD and there those quantities should not differ from their values in the global disk around the central mass  $M_*$ . We use the same assumption due to lack of a better alternative, realizing that it may however not be justified.

**Other resonances** Angular momentum and energy transferred to the disk at a resonance is removed from the binary's orbit. Resonances are classified by a pattern frequency  $\Omega_{l,m}$ .

We have an integral of motion  $h_{l,m} \equiv E_b - \Omega_{l,m} J_b$  (go to system co-rotating with resonance). Therefore

$$\dot{E}_b = \Omega_{l,m} \dot{J}_b = -\Omega_{l,m} T_{\text{visc}}. \quad (135)$$

Starting from the standard evolution equations we deduce

$$\dot{a} = -2a \sqrt{1-e^2} \frac{\Omega_{l,m}}{\Omega_b} \frac{T_{\text{visc}}}{J_b}, \quad (136)$$

and

$$\dot{e} = \frac{(1-e^2)}{e} \left[ 1 - \frac{\Omega_{l,m}}{\Omega_b} \sqrt{1-e^2} \right] \frac{T_{\text{visc}}}{J_b}. \quad (137)$$

#### 4.2.5 Criticism of Model

No "(microscopic) mechanism" or "understanding" of eccentricity growth. Here: Eccentricity growth is due to Keplerian parametrization of orbit. More realistically, expressions for the energy flux of the binary-disk interaction are needed. But for this one needs a detail understanding of the microscopic interaction of the binary with the disk.

In reference system of rotating disk: Jacobi constant is conserved. Relate it with binary! Possible, but here assumption is that the torque of the binary acts axial-symmetrically on the disk. This is only applicable for circular orbits. It seems inconsistent to apply it for eccentric orbits. The cheat goes as follows: The relation is in fact valid only after having getting rid of orbital variations of the dynamical variables by taking the average over one radial period of the motion. It may still be used for non-axial-symmetric torques in a first approximation since

Thus we faithfully assume that, even for eccentric orbits, the torque acts on average axially-symmetrically onto the disk. This is still not fully satisfactory, and more work is needed.

#### 4.2.6 Disc evolution - Resonances

##### APPLICABLE ONLY FOR SMALL ECCENTRICITIES

If the tidal interaction with the binary presents a strong barrier for the gas inflow, then mass accretion onto the binary is vanishingly small. This is the

case when the mass ratio is close to unity. For low values of  $q$ , tidal torques do not have to completely stop the mass inflow.

In the following we present a model for the migration of the secondary BH which allows to estimate the mass accretion. To this end, we use a (semi-)analytical expression for the tidal torque on the disk from the presence of the secondary mass (in the previous section we ignored the detailed form of the tidal torque). For a Keplerian disk the surface density evolution (121) is governed by the equation

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[ 3r^{1/2} \frac{\partial}{\partial r} \left( \nu \Sigma r^{1/2} \right) - \frac{2r^{3/2} \Sigma \tilde{T}_{\text{tid}}}{M_1^{1/2}} \right], \quad (138)$$

where we incorporated the tidal effect of the disk-secondary interaction through the injection rate of angular momentum per unit mass  $\tilde{T}_{\text{tid}}$ .

Goldreich and Tremaine in [6] calculated amplitudes of the torque produced by the individual azimuthal Fourier harmonics of the secondary potential. Assumptions: (no restriction to  $q$ ), and use epicycle approximation (nearly circular orbits). Chandrasekhar page 156 for parametrization. [...] Their result for the radial density torque is

$$\frac{dT}{dr} = \text{sign}(r-a) \frac{\kappa^2 r \Sigma}{2^3 A^4} \frac{M_2^2}{(a-r)^4} \left\{ \frac{2\Omega}{\kappa} K_0 \left( \frac{\kappa}{2|A|} \right) + K_1 \left( \frac{\kappa}{2|A|} \right) \right\}^2. \quad (139)$$

For a Keplerian orbit this simplifies to

$$\frac{dT}{dr} = \text{sign}(r-a) \frac{r \Sigma}{\Omega^2} \frac{M_2^2}{(a-r)^4} \frac{32}{81} \left\{ 2K_0 \left( \frac{2}{3} \right) + K_1 \left( \frac{2}{3} \right) \right\}^2 \quad (140)$$

$$\approx \text{sign}(r-a) f \frac{r \Sigma}{\Omega^2} \frac{M_2^2}{(a-r)^4} = \text{sign}(r-a) \Sigma f q^2 M_1 \frac{r^4}{(a-r)^4}, \quad (141)$$

with  $f \approx 2.5$ .

The (unperturbed, not taking epicycle into account) angular momentum of the secondary is  $L = M_2 a^2 \Omega$ . The torque exerted at each ring annulus  $T_r$  changes the angular momentum of the secondary according to (angular momentum exchange between the disk and the secondary may cause secular orbital evolution of the secondary)

$$\frac{dL}{dt} = -T_r. \quad (142)$$

**Semi-major axis evolution** Thus we find the change in orbital separation due to the torque acting at radius  $r$  (using  $\kappa(a) = 2\Omega(a)$ )

$$\begin{aligned} \dot{a} &= -\frac{2\Omega}{a\kappa^2 M_2} T_r \\ &= \text{sign}(a-r) \frac{2\pi \Sigma r dr}{2^3 \pi A^4} \frac{\Omega M_2}{a(a-r)^4} \left\{ \frac{2\Omega}{\kappa} K_0 \left( \frac{\kappa}{2|A|} \right) + K_1 \left( \frac{\kappa}{2|A|} \right) \right\}^2. \end{aligned}$$

For a Keplerian disk this reduces to

$$\frac{\dot{a}}{a} = 0.798 \frac{M_2 M_r}{M_1^2} \Omega \left( \frac{a}{a-r} \right)^4 \text{sign}(a-r),$$

where  $M_r = 2\pi\Sigma r dr$ .

Summing all contributions yields

$$\begin{aligned}\frac{\dot{a}}{a} &= 0.798 \frac{M_2}{M_1^2} \int_{R_{in}}^{R_{out}} M_r \Omega \left( \frac{a}{a-r} \right)^4 \text{sign}(a-r) \\ &= 2\pi \times 0.798 \frac{M_2}{M_1^2} \Omega a^4 \left[ \int_{R_{in}}^{a'} dr \Sigma \frac{r}{(a-r)^4} - \int_{a''}^{R_{out}} dr \Sigma \frac{r}{(a-r)^4} \right].\end{aligned}$$

Tentatively, pulling out  $\Sigma$  and setting  $a' = a - \delta$  and  $a'' = a + \delta$

$$\begin{aligned}\frac{\dot{a}}{a} &= 2\pi \times 0.798 \frac{M_2}{M_1^2} \Omega a^4 \Sigma \times \\ &\times \left[ \left[ \frac{a-3r}{6(r-a)^3} \right]_{r=R_{in}}^{r=a'} - \left[ \frac{a-3r}{6(r-a)^3} \right]_{r=a''}^{r=R_{out}} \right].\end{aligned}\quad (143)$$

**Eccentricity evolution** The eccentricity evolution reads

$$\frac{de}{dt} = - \left[ (\Omega_p - \Omega) - 2e^2 \Omega \left( 1 + \frac{d \log \kappa}{d \log r} \right) \right] \frac{T_r}{M_s e (a \kappa)^2} \quad (144)$$

For the Lindblad resonance we get

$$\frac{\dot{e}}{e} = \frac{\kappa^2 M_2 M_r}{8\pi |A|^5 a |a-r|^5} \left\{ \left[ 1 + \left( \frac{2\Omega}{\kappa} \right)^2 \right] K_0 \left( \frac{\kappa}{|A|} \right) + \left[ \frac{|A|}{\kappa} + \frac{4\Omega}{\kappa} \right] K_1 \left( \frac{\kappa}{|A|} \right) \right\}^2. \quad (145)$$

For the corotation resonances we get

$$\frac{\dot{e}}{e} = - \frac{\kappa^2 M_2 M_r}{8\pi |A|^5 a |a-r|^5} \frac{|A|}{2B} \left\{ \frac{2\Omega}{\kappa} K_0 \left( \frac{\kappa}{2|A|} \right) + K_1 \left( \frac{\kappa}{2|A|} \right) \right\}^2. \quad (146)$$

Evaluating the above equations for Keplerian disks results in

$$\frac{\dot{e}}{e} = 1.523 \frac{M_2 M_r}{M_1^2} \Omega \left( \frac{a}{|a-r|} \right)^5, \quad (147)$$

$$\frac{\dot{e}}{e} = -1.596 \frac{M_2 M_r}{M_1^2} \Omega \left( \frac{a}{|a-r|} \right)^5; \quad (148)$$

the positive term and the negative term come from the Lindblad and the corotation resonances, respectively.

Summing the contributions from successive rings we obtain (here for L-resonances)

$$\frac{\dot{e}}{e} = 2\pi \times 1.523 \frac{M_2}{M_1^2} \Sigma \Omega a^5 \left[ \int_{R_{in}}^{a'} dr \frac{r}{|a-r|^5} + \int_{a''}^{R_{out}} dr \frac{r}{|a-r|^5} \right] \quad (149)$$

$$= -2\pi \times 1.523 \frac{M_2}{M_1^2} \Sigma \Omega a^5 \left[ \left[ \frac{(a-4r)}{12(a-r)^4} \right]_{r=r_{in}}^{r=a'} - \left[ \frac{(a-4r)}{12(a-r)^4} \right]_{r=a''}^{r=r_{out}} \right]. \quad (150)$$

### 4.3 Plots

One may add to the above disk-driven orbital evolution equations the corresponding GW driven evolution equations (100) and (101). This coupled system of differential equations can be integrated numerically. Among the various ordinary differential equations solvers in Matlab, the ode23tb function performed best. This solver is designed for solving stiff ordinary differential equations. Indeed, during the latest stages of inspiral, the solution displays much variation within a short time interval.

As expected, at most values of  $a$  the disk-binary interaction dominates the GW emission which reduces the GW-driven merger time by several orders of magnitudes. The disk-binary dynamics reduces the binary's semi-major axis while at the same time increasing the orbit's eccentricity. At a critical semi-major axis (where  $\dot{a}_{\text{GW}} = \dot{a}_{\text{CDB}}$ ) the binary decouples from the disk and evolves (until coalescence) thereafter predominately under the emission of GWs.

Figure (1) shows a comparison between the purely GW-driven merger times (blue) and those where in addition disk interactions are taken into account (green). The red curve shows the remaining time to coalescence after the binary has decoupled from the gas and GW-emission has taken over. The system parameters can be seen in the graphic; as noted earlier the CBD values are taken to be those of the global disk.

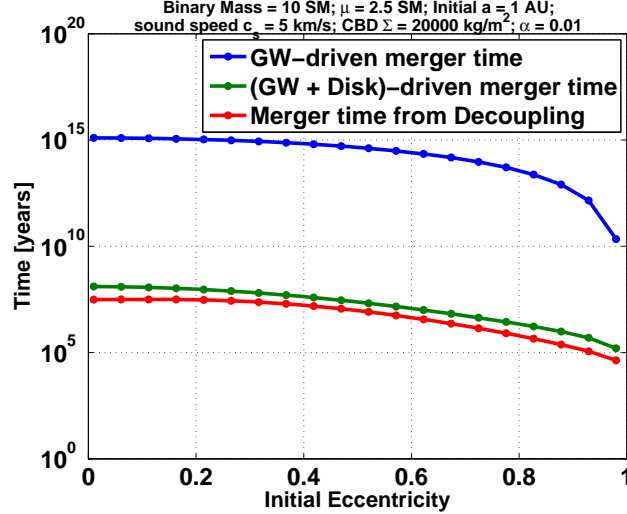


Figure 1: Merger times as a function of the initial binary eccentricity. The blue curve represents the merger times resulting from GW-driven decay, the green one resulting from both GW emission and disk-binary interaction. The red curve shows the time for which the binary evolution is dominated by GWs emission.

Figure (2) displays the AGN profile as described in section (4.2.1). The velocity dispersion  $\sigma$  was set to  $\sigma = 200$  km/s and  $f_g = 0.05$ .



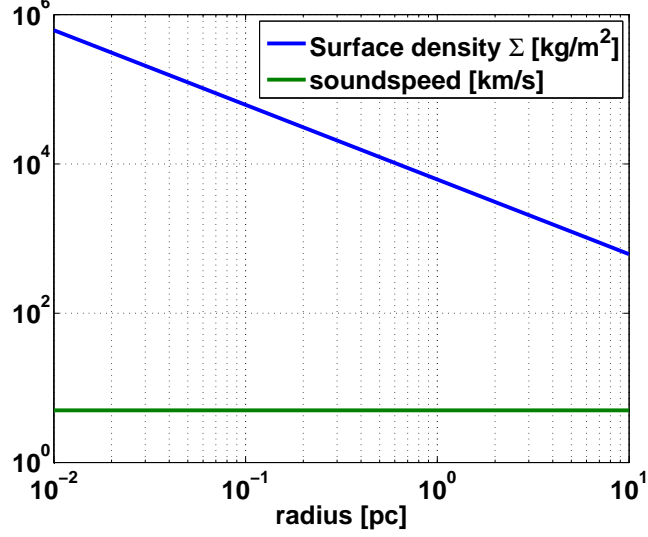


Figure 2: Key parameters as a function of the radius of the AGN disk.

In figure (3) the merger times for a binary are plotted as a function of the binary's location in an AGN disk having the profile of figure (2).

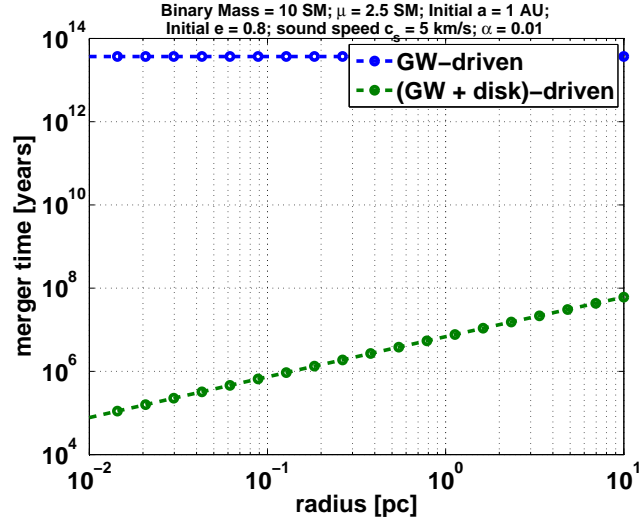


Figure 3: The merger times for a binary as a function of its location in the AGN disk (blue for GW-driven and green for (GW+gas)-driven).

In figure (4) the merger times for a binary are plotted as a function of the initial binary semi-major axis  $a_0$  for two different location of the binary in the AGN disk (blue at 0.01 pc, green at 10 pc). As  $a_0$  increases, the merger time decreases.

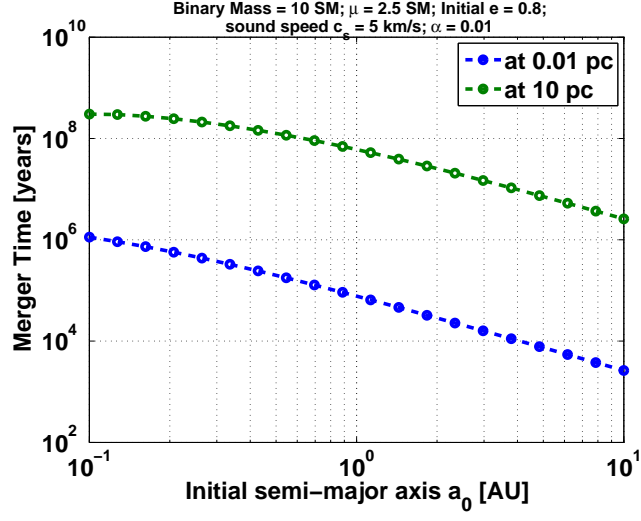


Figure 4: The merger times for a binary as a function of its initial semi-major axis. The two curves stand for two different binary locations in the background disk.

Figure (5) shows, as a function of the global disk radius, the lowest initial semi-major axis for which the merger time is less than  $10^6$  years (blue) or less than  $10^8$  years (green). *I.e.* for values  $a_0$  lying above the curve, the merger time is less than  $10^6$  or  $10^8$  years.

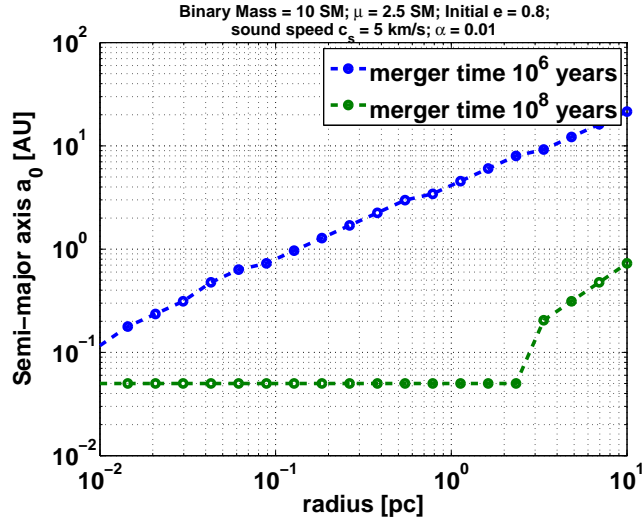


Figure 5: The curves show the smallest initial binary semi-major axis  $a_0$  for which the merger time is shorter than  $10^6$  and  $10^8$  years.

## 5 Merger rate ("steady state distribution")

Here some vocabulary:

- Galactic merger rates (number of coalescences per unit time within a galaxy)
- Local merger rate density (number of coalescences per unit time per unit volume in the local Universe, i.e. around redshift=0)
- Binary fraction  $f_b = \frac{N_b}{N_{sBH}}$

In this section we calculate the merger rate given a fixed radial mass distribution (thus not taking into account changes in the mass distribution due to e.g. dynamical friction).

We start with an initial stellar distribution. We assume that all stars above a critical mass have evolved into black holes. We further assume that a fraction  $f_b = \frac{2N_b}{N_{BH}}$  of the total number of BHs formed BH binaries.

### 5.1 Mass distributions

**Stellar distribution** The initial stellar mass distribution seems to follow a multiple power-law function [7]

$$f_{\text{IMF}}(m) = \begin{cases} k_0 \left(\frac{m}{M_\odot}\right)^{-0.3} & \text{if } m < 0.08M_\odot \\ k_1 \left(\frac{m}{M_\odot}\right)^{-1.3} & \text{if } 0.08M_\odot < m < 0.5M_\odot, \\ k_2 \left(\frac{m}{M_\odot}\right)^{-2.3} & \text{if } m > 0.5M_\odot \end{cases} \quad (151)$$

with normalization parameters  $k_0, k_1 = 0.08k_0$  and  $k_2 = 0.04k_0$ . The normalization is taken such that  $N_{s,\text{tot}} = \int_{m_{s,\text{min}}}^{m_{s,\text{max}}} dm f_{\text{IMF}}(m)$  and accordingly the parameter  $k_0$  is

$$k_0 = \frac{N_{s,\text{tot}}}{M_\odot} \left/ \left[ 0.56 - \frac{1}{0.7} \left(\frac{m_{s,\text{min}}}{M_\odot}\right)^{0.7} - \frac{0.04}{1.3} \left(\frac{m_{s,\text{max}}}{M_\odot}\right)^{-1.3} \right] \right. \quad (152)$$

The total stellar mass is

$$M_* = \int_{m_{s,\text{min}}}^{m_{s,\text{max}}} dm m f_{\text{IMF}} \quad (153)$$

$$= k_0 M_\odot^2 \left[ 0.22 - \frac{1}{1.7} \left(\frac{m_{s,\text{min}}}{M_\odot}\right)^{1.7} - \frac{0.04}{0.3} \left(\frac{m_{s,\text{max}}}{M_\odot}\right)^{-0.3} \right] \quad (154)$$

We adopt the "Nuker law" parametrization ([8]) for the stellar density profile  $\rho_*(r)$

$$\rho_*(r) \propto \left(\frac{r_b}{r}\right)^\gamma \left[ 1 + \left(\frac{r}{r_b}\right)^\alpha \right]^{\frac{\gamma-\beta}{\alpha}}, \quad (155)$$

We simplify this profile by using its asymptomatic slopes,

$$\rho_*(r) = \begin{cases} \rho_0 \left(\frac{r}{r_b}\right)^{-\gamma} & \text{if } r \leq r_b \\ \rho_0 \left(\frac{r}{r_b}\right)^{-\beta} & \text{if } r > r_b \end{cases}; \quad (156)$$

the parameter  $\alpha$  would parameterize the transition between the inner cusp and the outer power law. The break radius  $r_b$  is approximately on the order of the radius of influence of the SMBH ([9]), characterized as  $r_b = M_{\text{SMBH}}/\sigma_*^2$  ( $\sigma_*$  is the stellar dispersion). The normalization parameter  $\rho_0$  can be expressed as (we only consider models with  $\beta > 3$ )

$$\rho_0 = \frac{M_*}{4\pi r_b^3} \left( \frac{1}{3-\gamma} - \frac{1}{3-\beta} \right)^{-1}. \quad (157)$$

**BH distribution** If we assume that every star heavier than  $m_{\text{cr}}$  evolved into a BH, the total initial number of BHs is

$$N = \int_{m_{\text{s,cr}}}^{m_{\text{s,max}}} dm f_{\text{IMF}} \quad (158)$$

$$= k_0 M_\odot \left[ 0.56 - \frac{1}{0.7} \left( \frac{m_{\text{s,cr}}}{M_\odot} \right)^{0.7} - \frac{0.04}{1.3} \left( \frac{m_{\text{s,max}}}{M_\odot} \right)^{-1.3} \right] \quad (159)$$

$$= k M_*, \quad (160)$$

where we defined

$$k = \frac{1}{M_\odot} \frac{\left[ 0.56 - \frac{1}{0.7} \left( \frac{m_{\text{s,cr}}}{M_\odot} \right)^{0.7} - \frac{0.04}{1.3} \left( \frac{m_{\text{s,max}}}{M_\odot} \right)^{-1.3} \right]}{\left[ 0.22 - \frac{1}{1.7} \left( \frac{m_{\text{s,min}}}{M_\odot} \right)^{1.7} - \frac{0.04}{0.3} \left( \frac{m_{\text{s,max}}}{M_\odot} \right)^{-0.3} \right]}. \quad (161)$$

The total mass of all BHs is

$$M_{\text{BH}} = \int_{m_{\text{s,cr}}}^{m_{\text{s,max}}} dm m f_{\text{IMF}}. \quad (162)$$

The BH mass distribution is denoted as  $f_{\text{BH}}(m)$  and is normalized such that  $\int dm f_{\text{BH}}(m) = 1$ . We adopt a Salpeter mass function for the BH distribution

$$f_{\text{BH}}(m) = \xi_0 m^{-2.35}; \quad (163)$$

the normalization parameter  $\xi_0$  is then

$$\xi_0 = -\frac{1.35}{m_{\text{BH,max}}^{-1.35} - m_{\text{BH,min}}^{-1.35}}. \quad (164)$$

If  $N(r)$  denotes the total number of BHs inside some radius  $r$ , the number  $dN$  of BHs lying inside  $r$  with masses between  $m$  and  $m + dm$  is

$$dN = N(r) f_{\text{BH}}(m) dm \quad (165)$$

$$= k M_*(r) f_{\text{BH}}(m) dm, \quad (166)$$

where  $M_*(r)$  is the total stellar mass inside radius  $r$  ( $M_*(\infty) \equiv M_*$ ). Note that for the last equality we assumed that the mass distribution of the BHs is independent of the radius at which they reside (an assumption that may not be justified). We can write  $dN$  in the following form

$$dN = dm k f_{\text{BH}}(m) \int_0^r dr \rho_*(r) 4\pi r^2, \quad (167)$$

and this yields finally

$$\frac{dN}{dm} = \begin{cases} k f_{\text{BH}}(m) \frac{4\pi\rho_0}{3-\gamma} r_b^\gamma r^{3-\gamma} & \text{if } r \leq r_b \\ k f_{\text{BH}}(m) 4\pi\rho_0 r_b^3 \left[ \frac{1}{3-\gamma} + \frac{1}{3-\beta} \left[ \left( \frac{r}{r_b} \right)^{3-\beta} - 1 \right] \right] & \text{if } r > r_b \end{cases} \quad (168)$$

The number of BHs with masses between  $m$  and  $m + dm$  in a radial shell from radius  $r$  to  $r + dr$  is accordingly

$$\begin{cases} dm k f_{\text{BH}}(m) \frac{4\pi\rho_0}{3-\gamma} r_b^\gamma [(r + dr)^{3-\gamma} - r^{3-\gamma}] & \text{if } r \leq r_b \\ dm k f_{\text{BH}}(m) \frac{4\pi\rho_0}{3-\beta} r_b^3 \left[ \left( \frac{r+dr}{r_b} \right)^{3-\beta} - \left( \frac{r}{r_b} \right)^{3-\beta} \right] & \text{if } r > r_b \end{cases} \quad (169)$$

Recall also that the total number of BHs in a radial shell from radius  $r$  to  $r + dr$  is

$$\begin{cases} k \frac{4\pi\rho_0}{3-\gamma} r_b^\gamma [(r + dr)^{3-\gamma} - r^{3-\gamma}] & \text{if } r \leq r_b \\ k \frac{4\pi\rho_0}{3-\beta} r_b^3 \left[ \left( \frac{r+dr}{r_b} \right)^{3-\beta} - \left( \frac{r}{r_b} \right)^{3-\beta} \right] & \text{if } r > r_b \end{cases} \quad (170)$$

## 5.2 Rate per Galaxy

To determine the merger rate per galaxy, we add up the contributions from different radial shells. To this end, we partition the disk into  $\mathcal{I}_r$  intervals (we assume that the disk around the SMBH is truncated at 10 pc). The number of BHs within each radial shell  $[i\Delta r, (i+1)\Delta r]$ , where  $\Delta r = 10\text{pc}/|\mathcal{I}_r|$  is obtained from equation (170)

$$N_{r,i} = \begin{cases} k \frac{4\pi\rho_0}{3-\gamma} r_b^\gamma [((i+1)\Delta r)^{3-\gamma} - (i\Delta r)^{3-\gamma}] & \text{if } (i+1)\Delta r \leq r_b \\ k \frac{4\pi\rho_0}{3-\beta} r_b^3 \left[ \left( \frac{(i+1)\Delta r}{r_b} \right)^{3-\beta} - \left( \frac{i\Delta r}{r_b} \right)^{3-\beta} \right] & \text{if } i\Delta r > r_b \end{cases} \quad (171)$$

The average radius within each radial shell is

$$r_i = (i + 0.5)\Delta r. \quad (172)$$

### 5.2.1 BBH distributions within radial shell

For the moment we assume for simplicity a binary fraction of unity, *i.e.* the number of binaries is  $N/2$ , where  $N$  is the total number of BHs.

Within each radial shell we assume independent primary mass, mass ratio, orbital separation and eccentricity distributions. The following distributions refer to a single radial shell  $[r, r + dr]$ .

**Primary mass distribution** We adopt the IMF of Salpeter for the primary mass distribution. Thus, in a radial shell  $[r, r + dr]$ , two times the number of binaries with primary mass between  $m$  and  $m + dm$  is given by equation (169).

**Secondary mass distribution** The secondary mass distribution is determined by the distribution of the mass ratio  $q$ , assumed to follow a uniform distribution ([10],[11])

$$f(q) = \mu, \quad (173)$$

where  $\mu$  is a constant and  $0.1 \leq q \leq 1$ . The normalization  $\mu \int_{0.1}^1 dq = \frac{1}{2} N_r$  determines  $\mu$ ;  $N_r$  is the total number of BHs in the shell  $[r, r + dr]$ , see equation (171).

**Orbital separation distribution** The distribution of the initial orbital separation  $a_0$  is assumed to be logarithmically flat ([10],[11])

$$f(a_0) = \chi_0/a_0, \quad (174)$$

between the limits 0.01 AU and 500 AU. Normalizations gives  $\chi_0 = \frac{N_r}{2 \log 50000}$ .

**Orbital eccentricity distribution** We choose the distribution of the initial orbital eccentricity  $e_0$  to follow a thermal distribution

$$f(e_0) = \varsigma_0 e_0, \quad (175)$$

between the limits 0 and 1. Normalization gives  $\varsigma_0 = N_r$ .

### 5.2.2 Rate within radial shell

In this section we determine the merger rate for a radial shell  $[r, r + dr]$ . In what follows, we partition the distribution functions  $x$  into discrete intervals indexed by  $\mathcal{I}_x$ .

**Primary mass** The number of primary BHs within the mass bin  $[m_{\text{BH,min}} + i\Delta M, m_{\text{BH,min}} + (i+1)\Delta M]$ , where  $\Delta M = (m_{\text{BH,max}} - m_{\text{BH,min}})/|\mathcal{I}_M|$  and  $i \in \mathcal{I}_M$ , is obtained by integrating equation (169)

$$N_{M,i} = \frac{4\pi k \rho_0 \xi_0}{1.35} \left[ (m_{\text{BH,min}} + i\Delta M)^{-1.35} - (m_{\text{BH,min}} + (i+1)\Delta M)^{-1.35} \right] \times \\ \times \begin{cases} \frac{1}{3-\gamma} r_b^\gamma \left[ (r+dr)^{3-\gamma} - r^{3-\gamma} \right] & \text{if } r \leq r_b \\ \frac{1}{3-\beta} r_b^3 \left[ \left( \frac{r+dr}{r_b} \right)^{3-\beta} - \left( \frac{r}{r_b} \right)^{3-\beta} \right] & \text{if } r > r_b \end{cases}. \quad (176)$$

The average mass within this mass bin is

$$M_i = \frac{1.35}{0.35} \frac{[(m_{\text{BH,min}} + i\Delta M)^{-0.35} - (m_{\text{BH,min}} + (i+1)\Delta M)^{-0.35}]}{[(m_{\text{BH,min}} + i\Delta M)^{-1.35} - (m_{\text{BH,min}} + (i+1)\Delta M)^{-1.35}]}. \quad (177)$$

**Mass ratio** The number of BBH within the mass ratio bin  $[0.1 + i\Delta q, 0.1 + (i+1)\Delta q]$ , where  $\Delta q = 0.9/|\mathcal{I}_q|$  and  $i \in \mathcal{I}_q$ , is

$$N_{q,i} = \frac{10}{18} N_r \Delta q. \quad (178)$$

The average mass ratio within this mass ratio bin is

$$q_i = (i + 0.5)\Delta q + 0.1. \quad (179)$$

**Orbital separation** The number of BBH within the orbital separation bin  $[0.01\text{AU} + i\Delta a, 0.01\text{AU} + (i+1)\Delta a]$ , where  $\Delta a = 499.99\text{AU}/|\mathcal{I}_{a_0}|$  and  $i \in \mathcal{I}_{a_0}$ , is

$$N_{a_0,i} = \chi_0 \log \left( \frac{0.01\text{AU} + (i+1)\Delta a}{0.01\text{AU} + i\Delta a} \right). \quad (180)$$

The average  $a_0$  within this bin is

$$a_{0,i} = \frac{\Delta a}{\log \left( \frac{0.01\text{AU} + (i+1)\Delta a}{0.01\text{AU} + i\Delta a} \right)}. \quad (181)$$

**Orbital eccentricity** The number of BBH within the eccentricity bin  $[i\Delta e_0, (i+1)\Delta e_0]$ , where  $\Delta e_0 = 1/|\mathcal{I}_{e_0}|$  and  $i \in \mathcal{I}_{e_0}$ , is

$$N_{e_0,i} = \varsigma_0 (i + 0.5) (\Delta e_0)^2. \quad (182)$$

The average  $e_0$  within this bin is

$$e_{0,i} = \frac{((i+1)\Delta e_0)^3 - (i\Delta e_0)^3}{3(i+0.5)(\Delta e_0)^2}. \quad (183)$$

**Merger rate for a radial shell** The total merger rate resulting from a radial shell is

$$\mathcal{R}_r = N_r \sum_{\alpha} \frac{N_{\alpha}}{N_r^4} \frac{1}{\tau_{\text{merger},\alpha}} \quad (184)$$

where the sum goes over all  $\alpha \in \mathcal{I}_M \times \mathcal{I}_q \times \mathcal{I}_{a_0} \times \mathcal{I}_{e_0}$ . Note that  $N_{\alpha} = N_{\alpha_1} N_{\alpha_2} N_{\alpha_3} N_{\alpha_4}$ .

### 5.2.3 Merger rate for galaxy

We set the model parameters to the fiducial values  $M_{\text{SMBH}} = 1 \times 10^6 M_{\odot}$ ,  $\gamma = 1.5$ ;  $\beta = 3.2$ ;  $\sigma_* = 30 \text{ km/s}$ ;  $m_{\text{s,max}} = 50000 M_{\odot}$ ;  $m_{\text{s,min}} = 0.01 M_{\odot}$ ;  $m_{\text{s,cr}} = 5 M_{\odot}$ ;  $m_{\text{BH,max}} = 50 M_{\odot}$ ;  $m_{\text{BH,min}} = 5 M_{\odot}$ ;  $N_{\text{s,tot}} = 20000$ ; we use the disk model of section (4.2) and use partitions  $|\mathcal{I}_r| = 20$  and  $|\mathcal{I}_M| = |\mathcal{I}_q| = |\mathcal{I}_{a_0}| = |\mathcal{I}_{e_0}| = 2$ . The galactic merger rate is then obtained by summing up the rate (184) for each shell. We obtain a rate of  $\mathcal{R} = 0.02 \frac{1}{\text{year}}$ . The rate is most sensitive to the total number of initial stars  $N_{\text{s,tot}}$ . Note that in the calculation we assumed that all BHs paired up to binaries, which is clearly not justified.

## 6 Merger rate ("Dynamical capture")

Gaussian velocity distribution.

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