Compact binaries in astrophysical environments

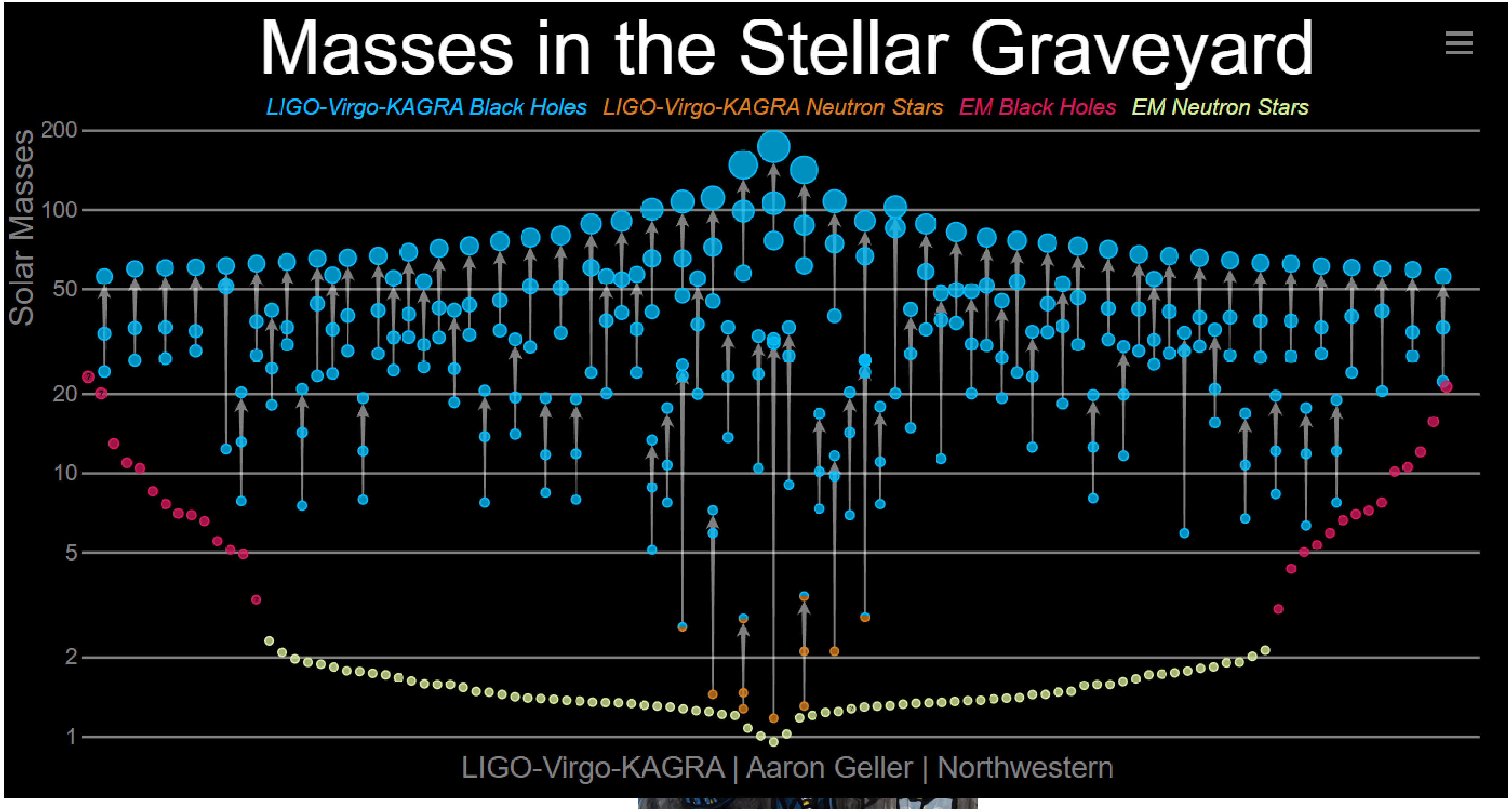
Caio F. B. Macedo

Outline

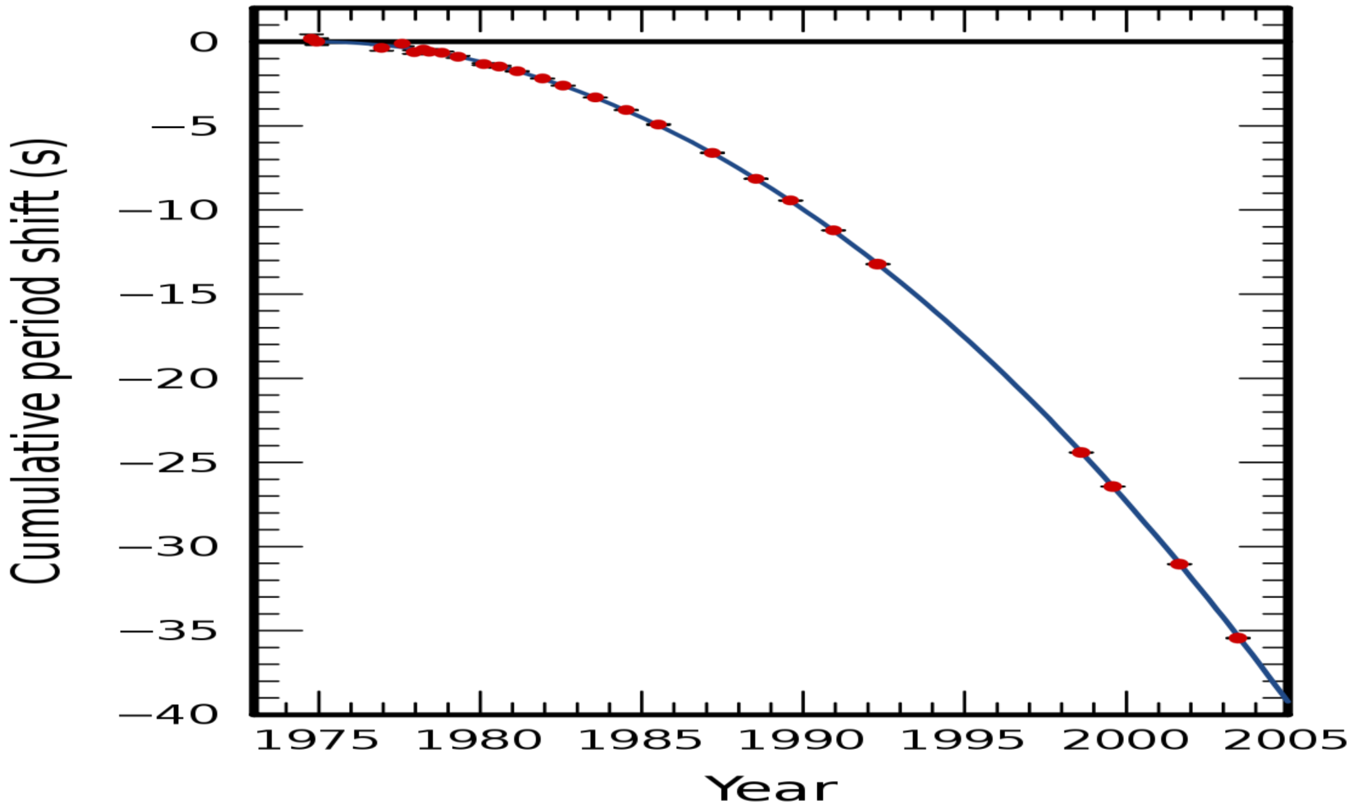
- General motivations
- Physical setups
- Binaries in environments
- Final remarks

General motivations

Main targets for GW detectors



Time passes, and the shift tells

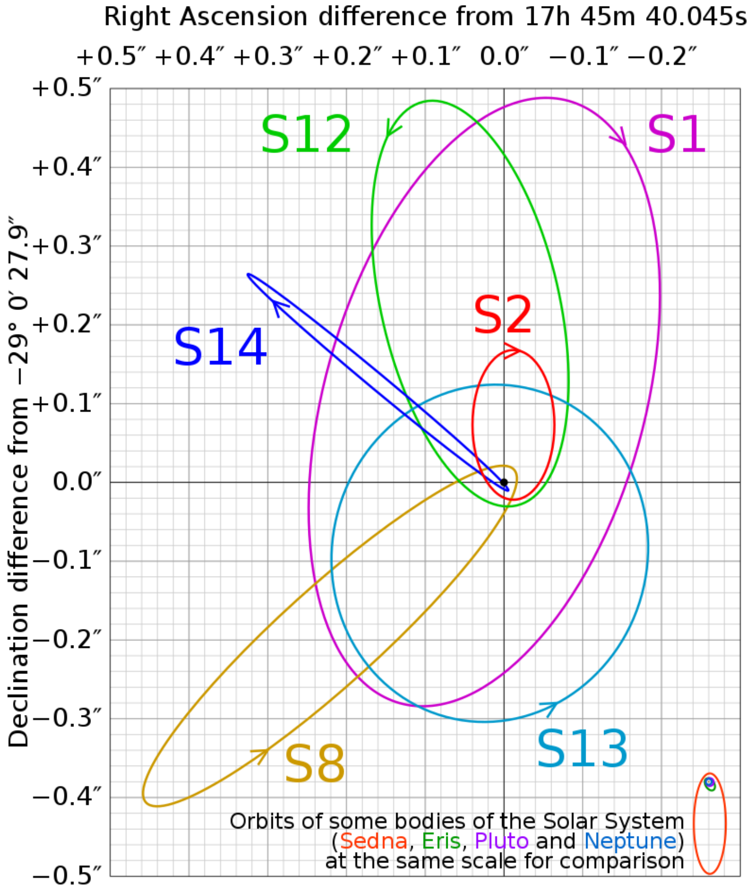


$$\frac{\dot{T}}{T} = \frac{3}{2}\,\frac{Energy\ Lost}{Orbital\ energy}$$

Accretion disks, plasmas environments and fuzzy dark matter

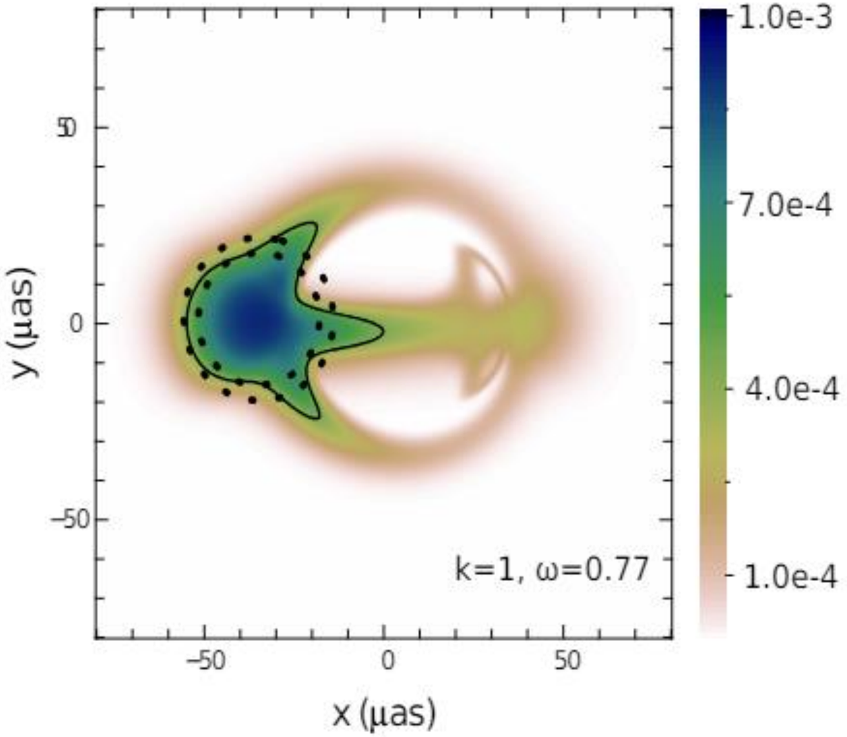
Barausse *et. al* PRD **89**, 104059 (2014), Wayne Hu, Rennan Barkana, and Andrei Gruzinov Phys. Rev. Lett. 85, 1158 (2000)

Environmental forces play an IMPORTANT role

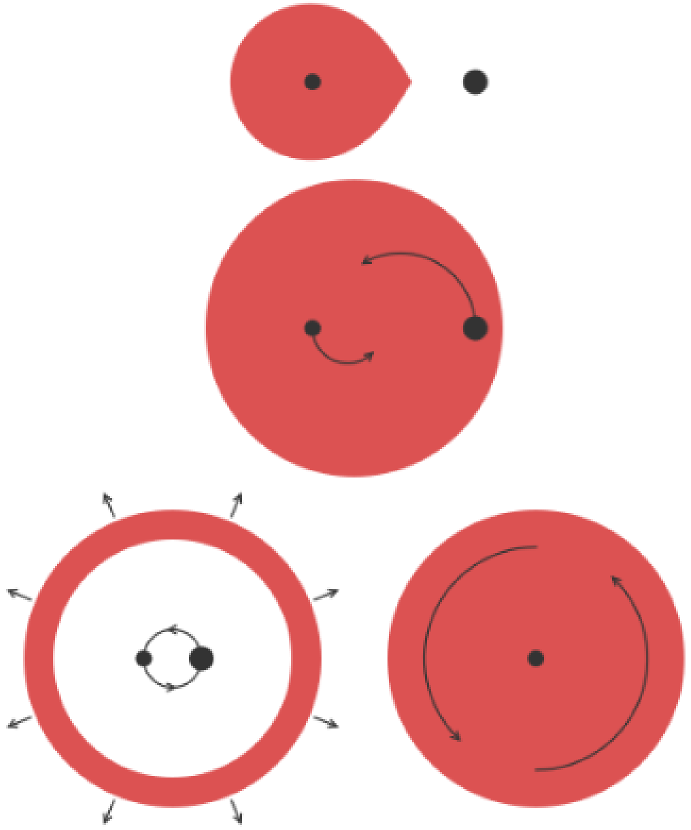


GRAVITY Collaboration

Boson stars and common envelopes



Vicent et al. Class.Quant.Grav. 33 (2016) 10, 105015

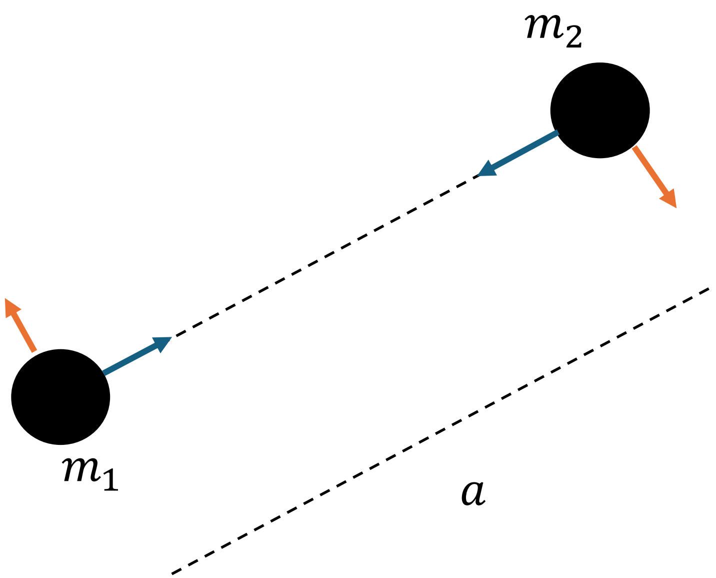


Ivanova et al., AARev., 21, 59 (2013)

Physical Setups

Physical setups

Newtonian elements



$$\ddot{\mathbf{r}} = f_1\dot{\mathbf{r}} + f_2\dot{\mathbf{R}} + f_3\mathbf{r}$$
$$\ddot{\mathbf{R}} = f_4\dot{\mathbf{r}} + f_5\dot{\mathbf{R}} + f_6\mathbf{r}$$

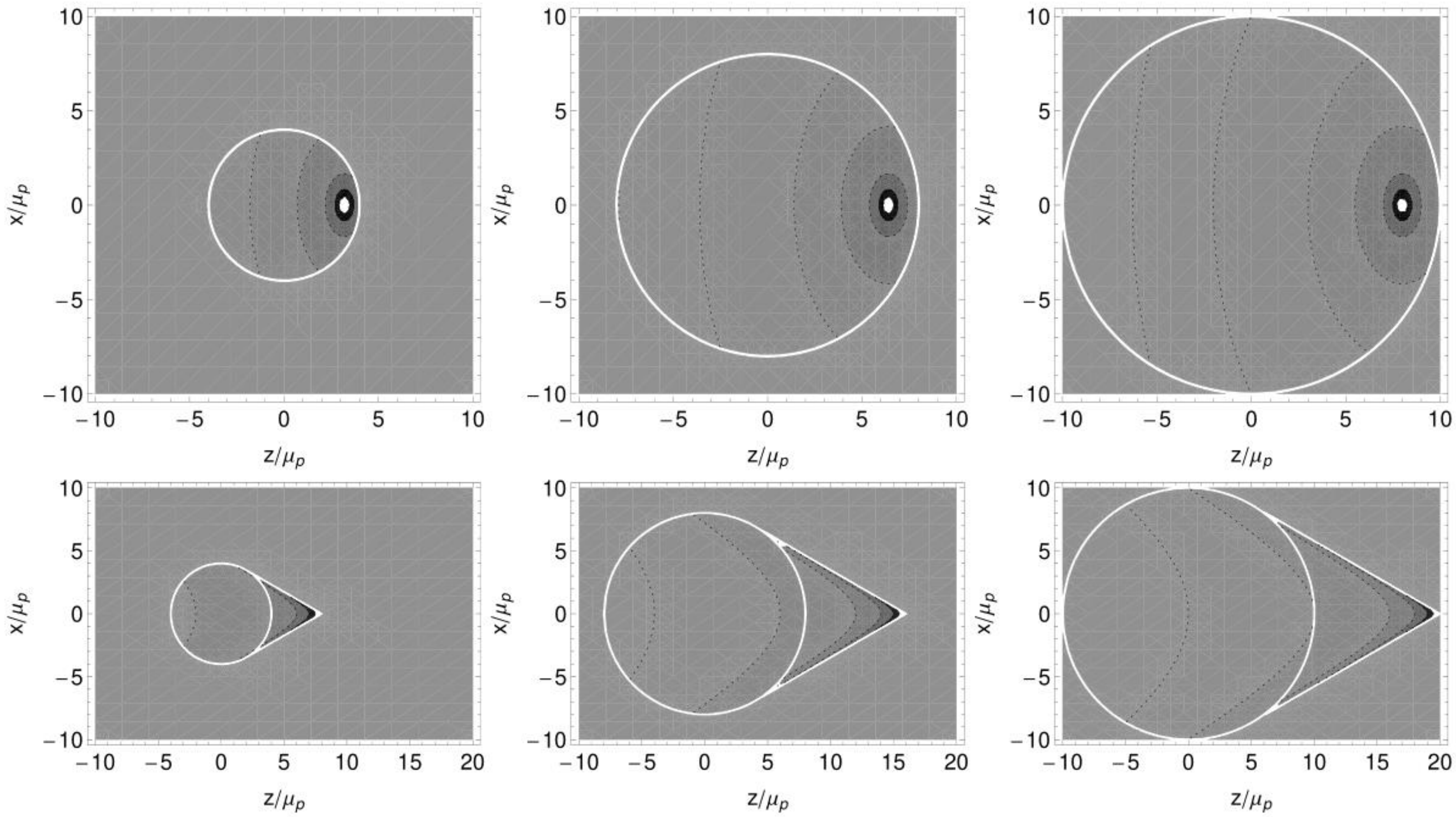
$$\mathbf{F}_{\mathrm{d},i} = -G^2 m_i^2 \rho I_{\mathrm{d}}(v_i)\dot{\mathbf{r}}_i$$

$$f_1 = -\frac{G^2 M q\rho(I_{\mathrm{a1}} + I_{\mathrm{a2}} + I_{\mathrm{d1}} + I_{\mathrm{d2}})}{(q+1)^2},$$
$$f_2 = \frac{G^2 M\rho[I_{\mathrm{a1}} + I_{\mathrm{d1}} - q(I_{\mathrm{a2}} + I_{\mathrm{d2}})]}{q+1},$$
$$f_3 = GM\left\{\frac{G^3 M q\rho^2(I_{\mathrm{a1}} - qI_{\mathrm{a2}})[I_{\mathrm{a1}} + I_{\mathrm{d1}} - q(I_{\mathrm{a2}} + I_{\mathrm{d2}})]}{(q+1)^4} - \frac{1}{r^3}\right\},$$
$$f_4 = \frac{G^2 M q\rho[q(I_{\mathrm{a2}} - I_{\mathrm{d2}}) - I_{\mathrm{a1}} + I_{\mathrm{d1}}]}{(q+1)^3},$$
$$f_5 = -\frac{G^2 M\rho\left[q^2(I_{\mathrm{a2}} + I_{\mathrm{d2}}) + I_{\mathrm{a1}} + I_{\mathrm{d1}}\right]}{(q+1)^2},$$
$$f_6 = -\frac{G^4 M^2 q\rho^2(I_{\mathrm{a1}} - qI_{\mathrm{a2}})\left[q^2(I_{\mathrm{a2}} + I_{\mathrm{d2}}) + 2q(I_{\mathrm{a1}} + I_{\mathrm{a2}}) + I_{\mathrm{a1}} + I_{\mathrm{d1}}\right]}{(q+1)^5}.$$

Physical setups

Newtonian elements: Dynamical friction

(Chandrasekhar, APJ (1943)), (Ostriker, astro-ph/9810324 (1998))

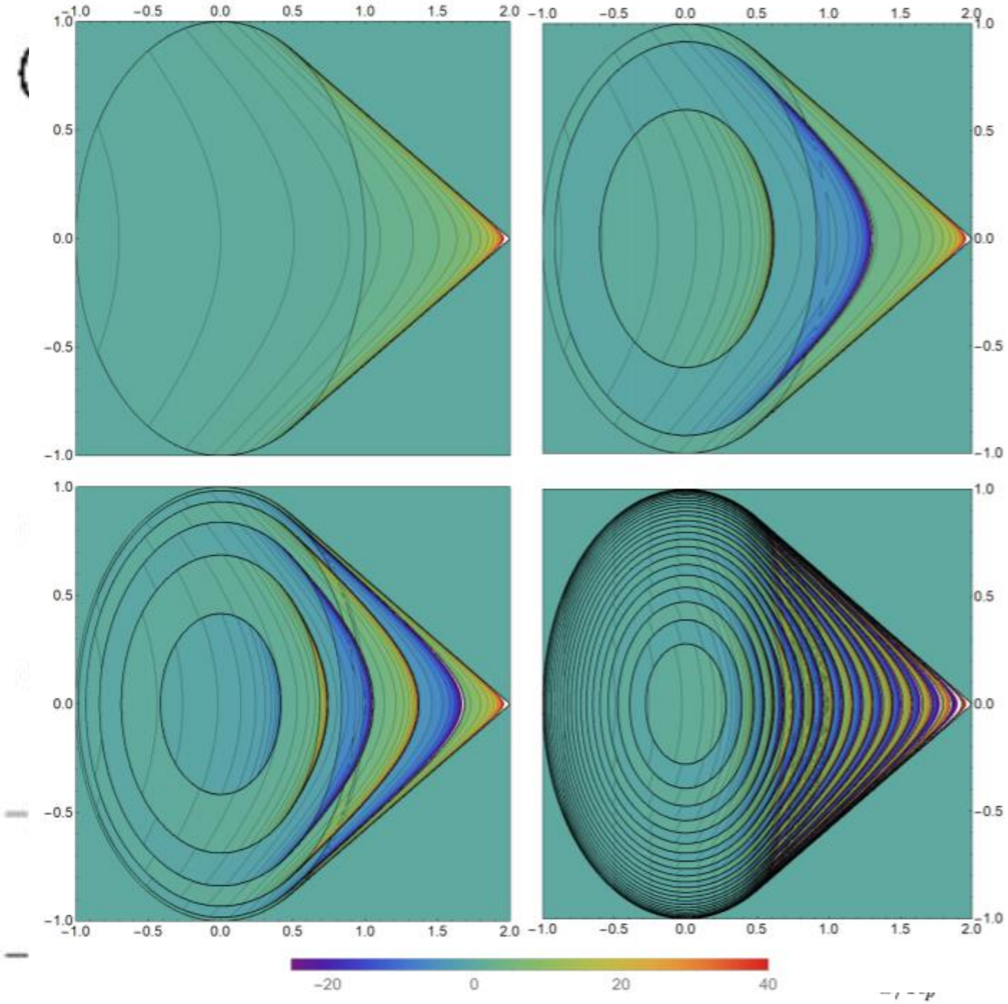


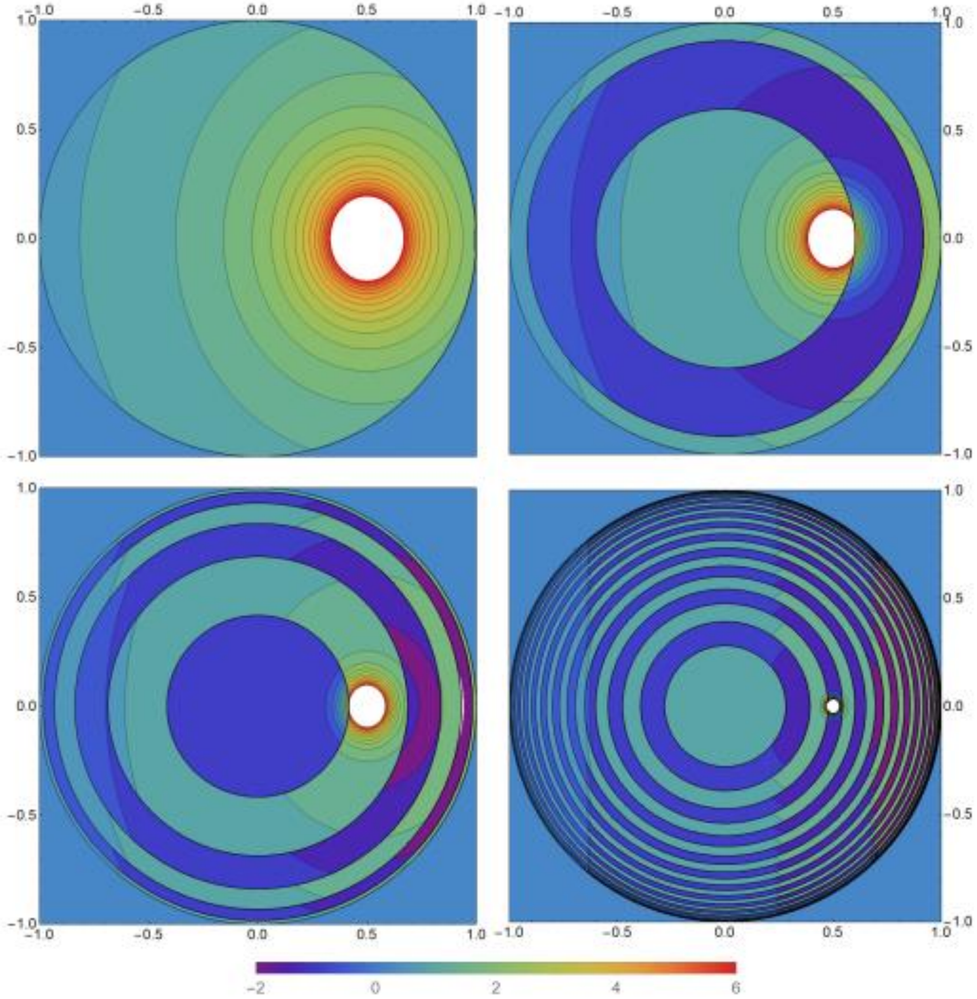
Physical setups

Newtonian elements: Dynamical friction in other scenarios

Kim&Kim, 0705.0084 (2007); Kim et al. 0804.2010 (2018); Vicente et. al 1905.06353 (2019)

“These are my principles. If you don’t like them, I have others”.





Physical setups

GR elements: Dynamical friction and scattering amplitudes

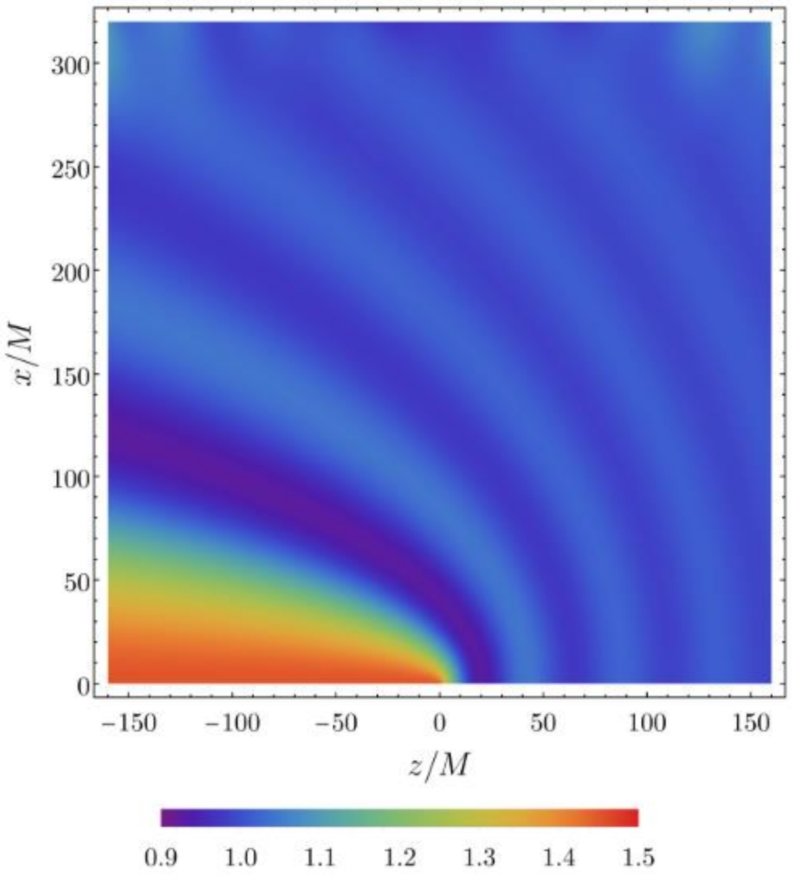
Traykova *et al. Phys. Rev. D 104, 103014 (2021), Vicente and Cardoso. Phys.Rev.D* 105 8, 083008 (2022), *Traykova et al.,Phys.Rev.D 108 12, L121502 (2023)*

$$\dot{E}_{\rm BH} = \frac{\pi \hbar \omega n}{\mu k_\infty} \sum_{\ell,m} (2\ell+1) \frac{(\ell-m)!}{(\ell+m)!} ({\rm Ps}_\ell^m)^2 \left(1 - \left|\frac{R}{I}\right|^2\right).$$

$$P_S^i(t') = \int_{S_{t'}} dV_3 T^{\alpha i} N_\alpha.$$

↓

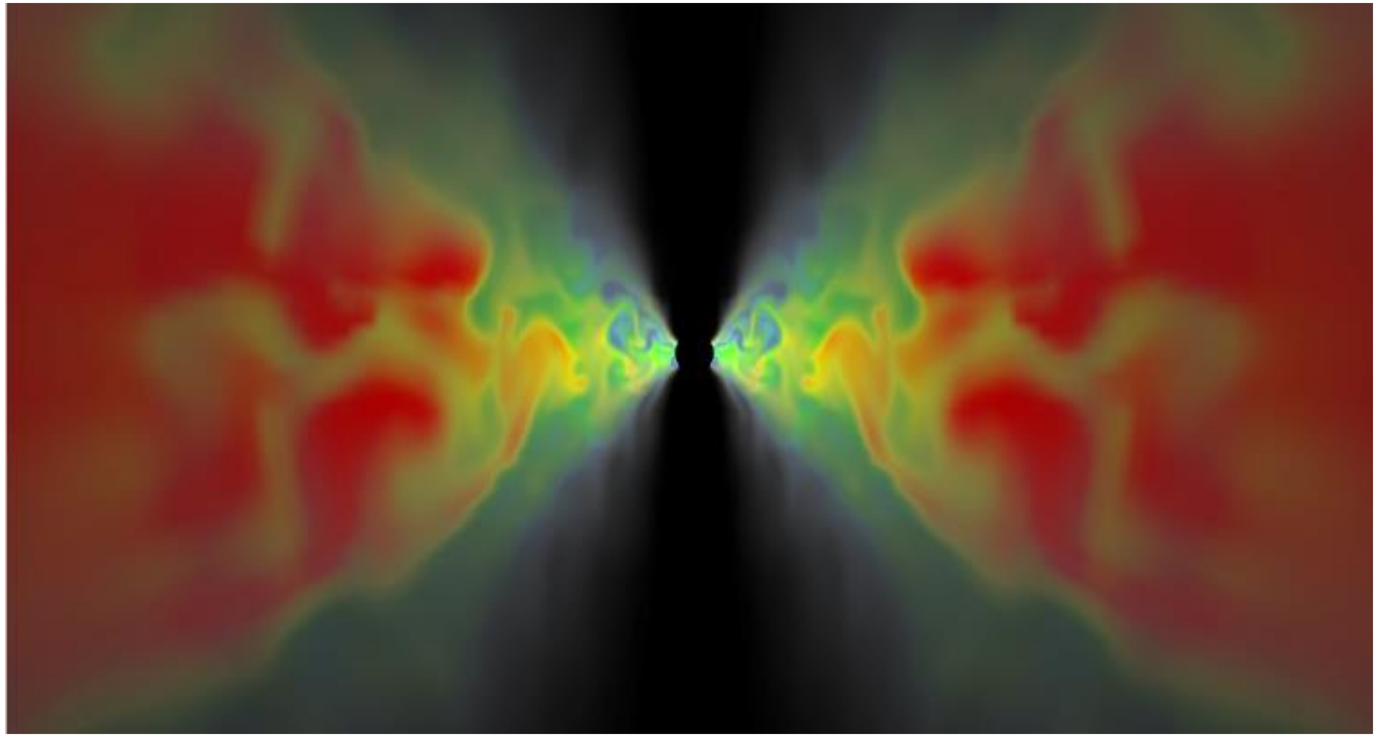
$$\boldsymbol{F}' = -\frac{4\pi M^2 \rho \boldsymbol{v}}{v^3} \log\left(\sqrt{1 + \frac{b_{\rm max}^2}{(M/v^2)^2}}\right)$$

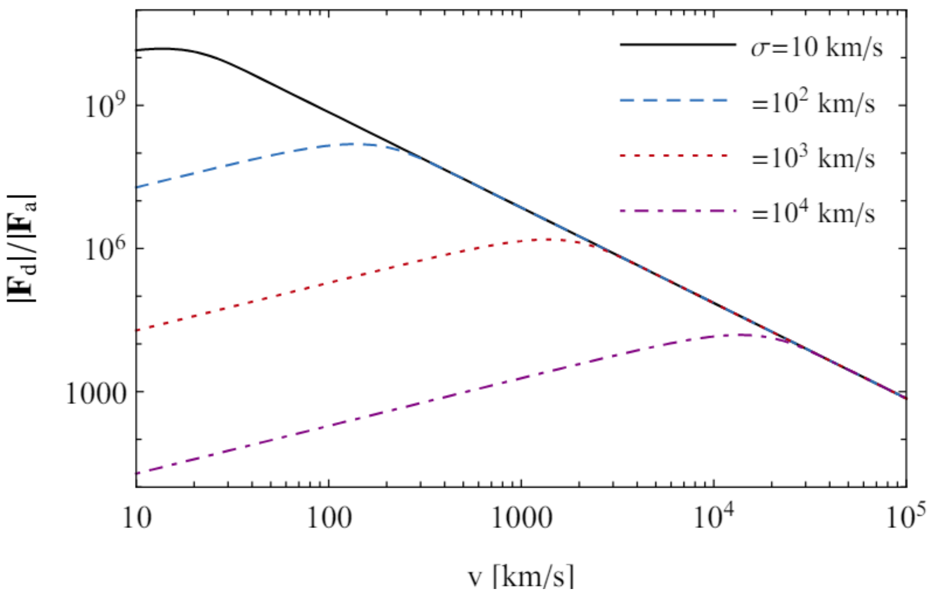


Note that the Chandrasekhar case is recovered

Physical setups

Newtonian(-ish) elements: Accretion





$$m_i\ddot{\mathbf{r}}_i + \dot{m}_i\dot{\mathbf{r}}_i = \pm\frac{Gm_1m_2}{r^3}\mathbf{r} + \mathbf{F}_i$$

E.g. Bondi-Hoyle-Littleton

$$\dot{m}_i = 4\pi G^2\rho\frac{m_i^2}{(v_i^2 + c_s^2)^{3/2}}$$

Physical setups

(Post-)Newtonian elements: quadru and octupole emissions

For ***gravitational waves***, we have

$$\langle \dot{E} \rangle = -\frac{32}{5} \frac{G^4 m_1^2 m_2^2 M}{a^5 (1-e^2)^{7/2}} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right)$$

$$\langle \dot{L} \rangle = -\frac{32}{5} \frac{G^{7/2} m_1^2 m_2^2 M^{1/2}}{a^{7/2} (1-e^2)^2} \left(1 + \frac{7}{8} e^2 \right) .$$

$$\frac{da}{dt} = -\frac{64}{5} \frac{G^3 \mu M^2}{c^5 a^3 (1-e^2)^{\frac{7}{2}}} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right), \downarrow$$

$$\frac{de}{dt} = -\frac{304}{15} \frac{G^3 \mu M^2}{c^5 a^4 (1-e^2)^{\frac{5}{2}}} \left(1 + \frac{121}{304} e^2 \right). \downarrow$$

Emission of gravitational waves ***circularizes*** orbits.

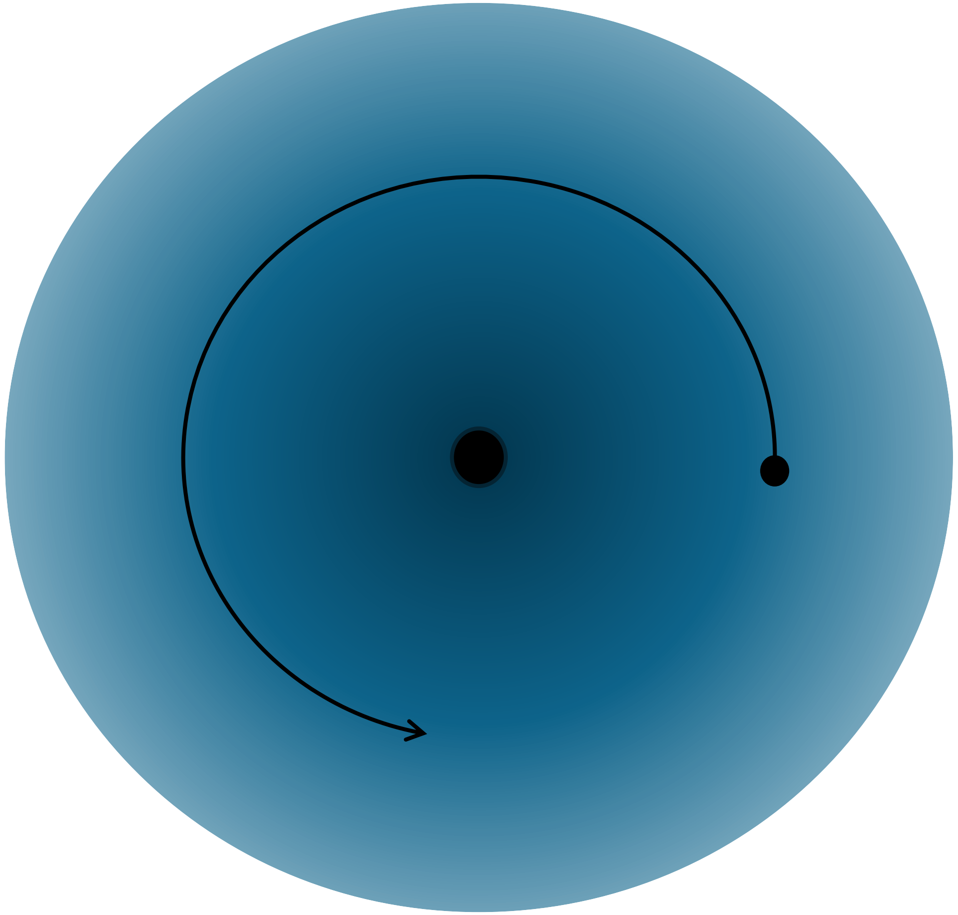
Physical setups

Radiation: scalar fields, black holes and particles

Macedo et al. 2013, Duque et al. 2023

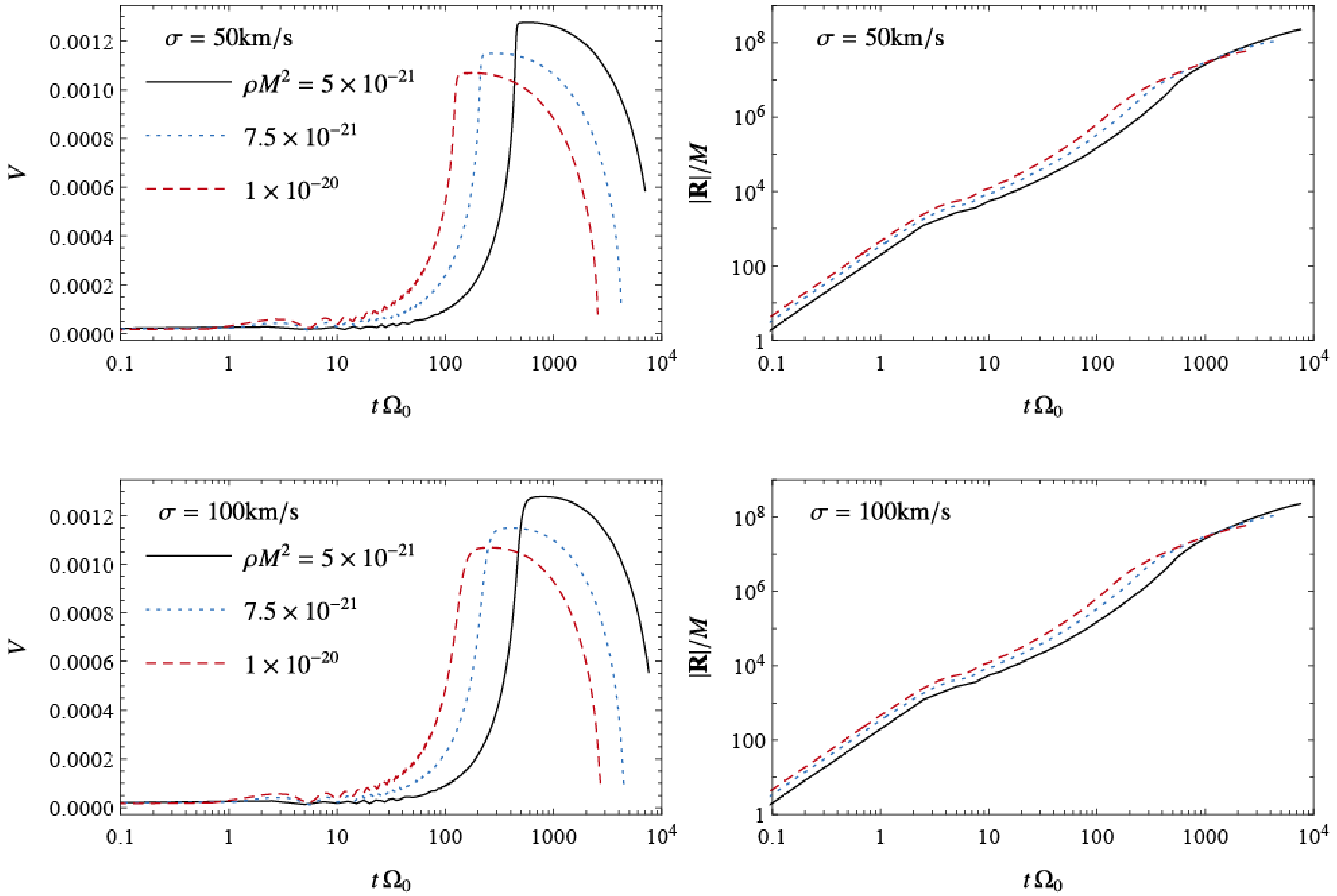
$$G_{\mu\nu} = 8\pi T_{\mu\nu}, \qquad \Box_g \Phi = \frac{\partial V}{\partial \Phi^*}$$

$$g_{\mu\nu} \approx \widehat{g}_{\mu\nu} + q\,\delta g_{\mu\nu}, \qquad \Phi \approx \widehat{\Phi} + q\,\delta\Phi$$



Binaries in environments

Boost in the center of mass



$V \sim 350\text{km/s}$

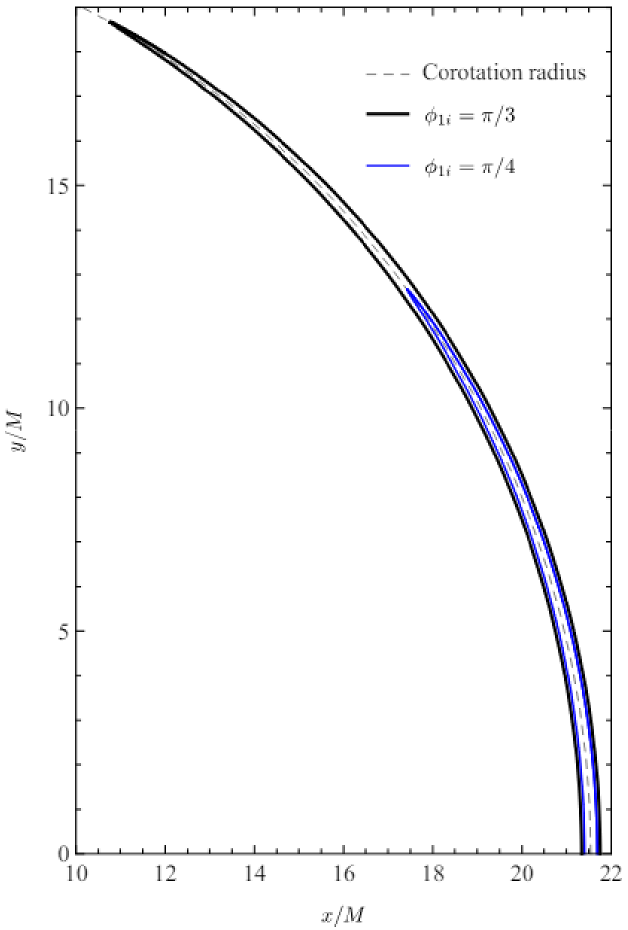
Binaries could escape galaxies!

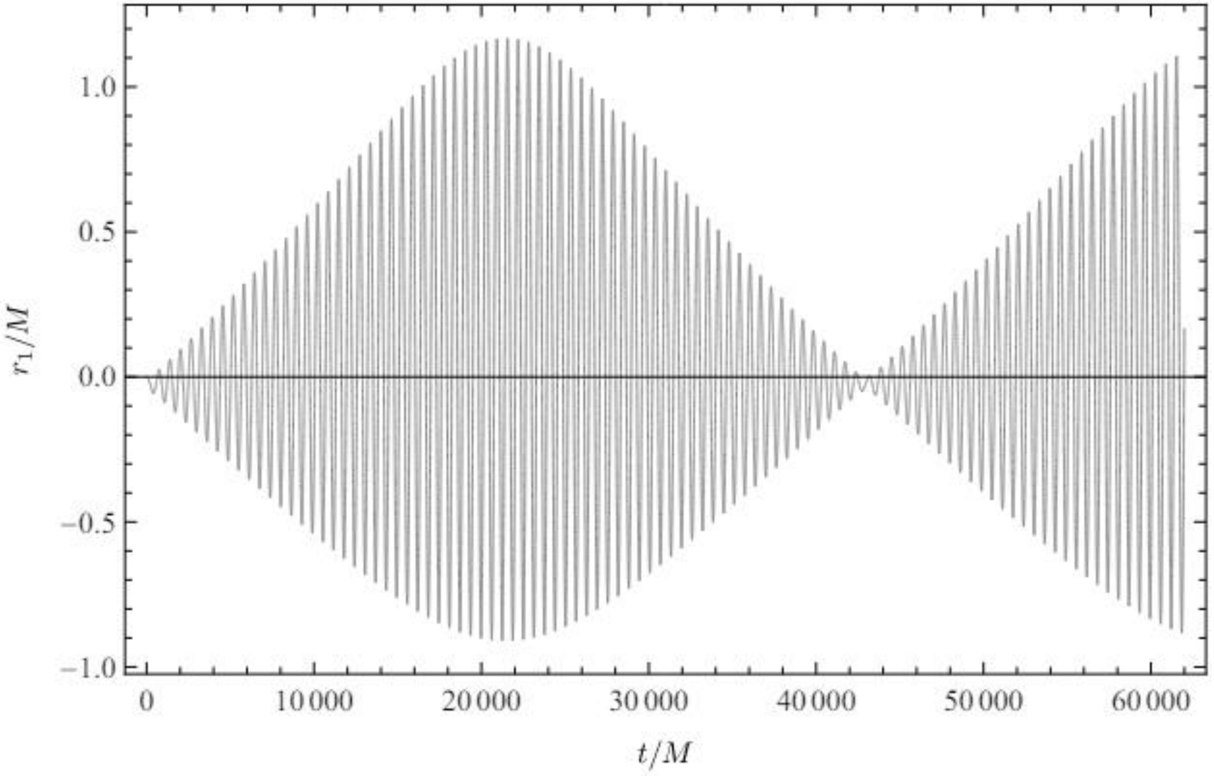
$$T_{\max} = 6 \left(\frac{M_\odot}{M} \right)^3 \left(\frac{10^{-6} \rho_{\text{water}}}{\rho} \right)^2 \text{ years}$$

Orbital dynamics

Ferreira et al.

A time dependent background idynamics introduces richer orbital dynamics





Eccentricity evolution and dynamical friction

Cardoso, CFBM, Vicente 2010.1515 (2021)) (Roedig&Sesana 1111.3742 (2012))

Considering dominant terms

$$\langle \dot{a} \rangle = -k\rho\sqrt{\frac{G\,a^5}{M}}\left(1 + \frac{3e^2}{4} + \mathcal{O}(e^4)\right),$$
$$\langle \dot{e} \rangle = \frac{3}{2}k\rho\sqrt{\frac{G\,a^3}{M}}e\left(1 + \frac{3e^2}{8} + \mathcal{O}(e^4)\right).$$

$$\frac{da}{de} = -\frac{2a}{3e}\left(1 + \frac{3}{8}e^2 + \mathcal{O}(e^3)\right)$$

Therefore, the environment favors eccentric motion! Considering both GW and the environment

$$\frac{da}{de} = \frac{6a\left(5c^5k\rho\sqrt{GMa^{11}} + 32G^3M^4\right)}{e\left(304G^3M^4 - 45c^5k\rho\sqrt{GMa^{11}}\right)}$$

→ ***Critical distance!***

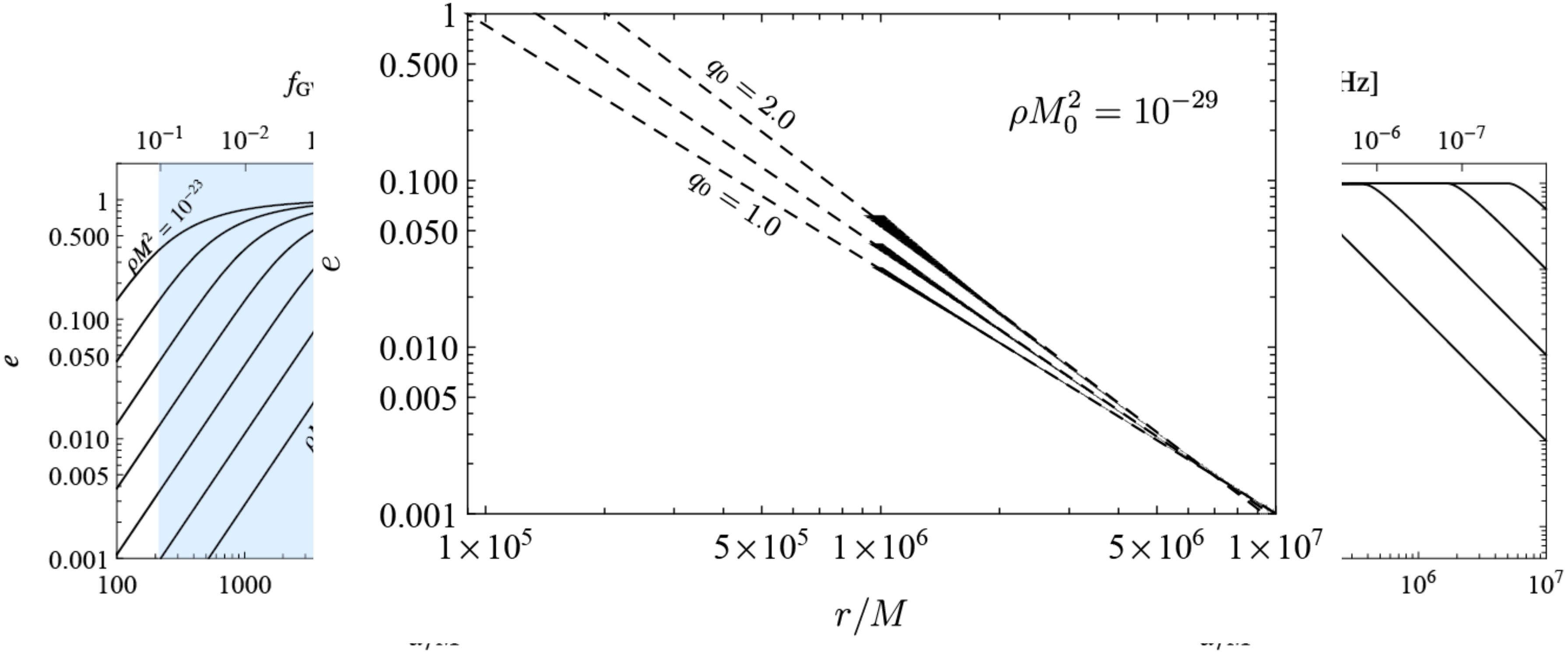
Eccentricity evolution and dynamical friction

Cardoso, CFBM, Vicente 2010.1515 (2021)) (Roedig&Sesana 1111.3742 (2012))

$$\frac{a_c}{\left(\frac{100GM_\odot}{c^2}\right)} = 3\times 10^4\, k^{-2/11}\left(\frac{M}{100M_\odot}\right)^{7/11}\left(\frac{\rho_{10}}{\rho}\right)^{2/11}$$

$$\rho_{10} = 10^{-10}\mathrm{g\,cm}^{-3}$$

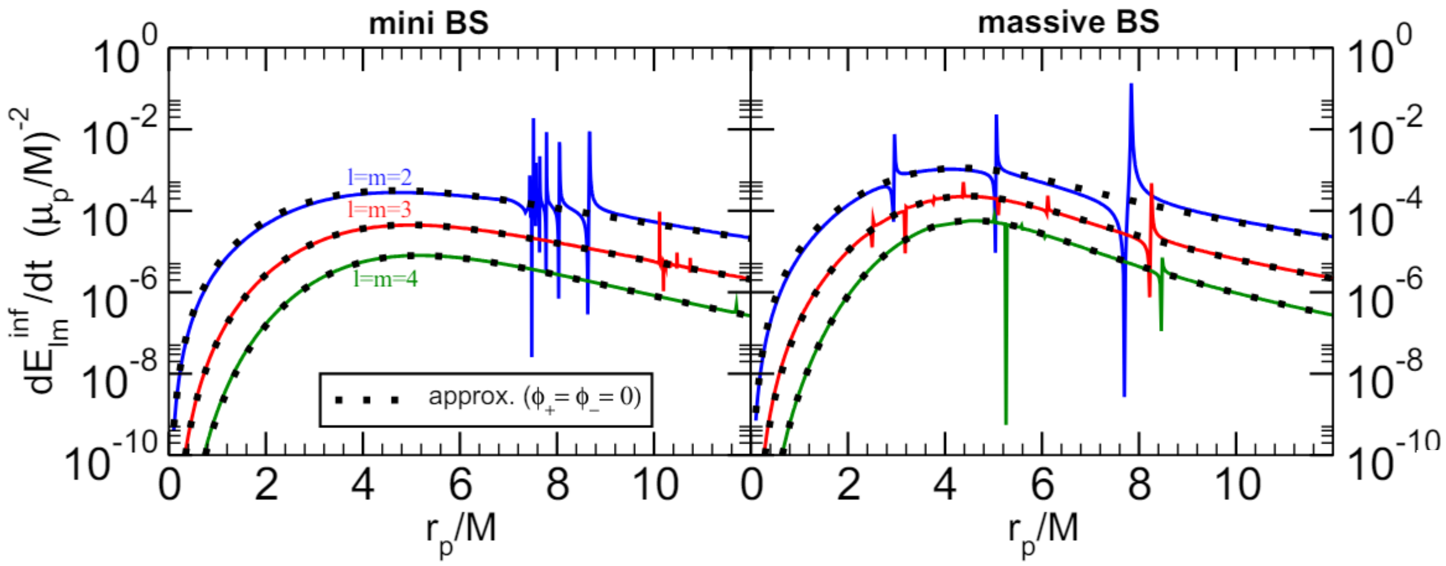
What about the evolution?



$$\frac{G^3}{c^6}\rho M^2 = 1.6\times 10^{-24}\frac{\rho}{\rho_{10}}\left(\frac{M}{100M_\odot}\right)^2$$

Mode excitation and dephasing

Macedo et al. Phys.Rev.D 88 6, 064046 (2013) & Astrophys.J. 774 (2013).



$$\dot{E} = \dot{E}_0 + h(t)\mathcal{H}\left[\delta t_{\rm res}^2 - (t - t_{\rm res})^2\right]$$

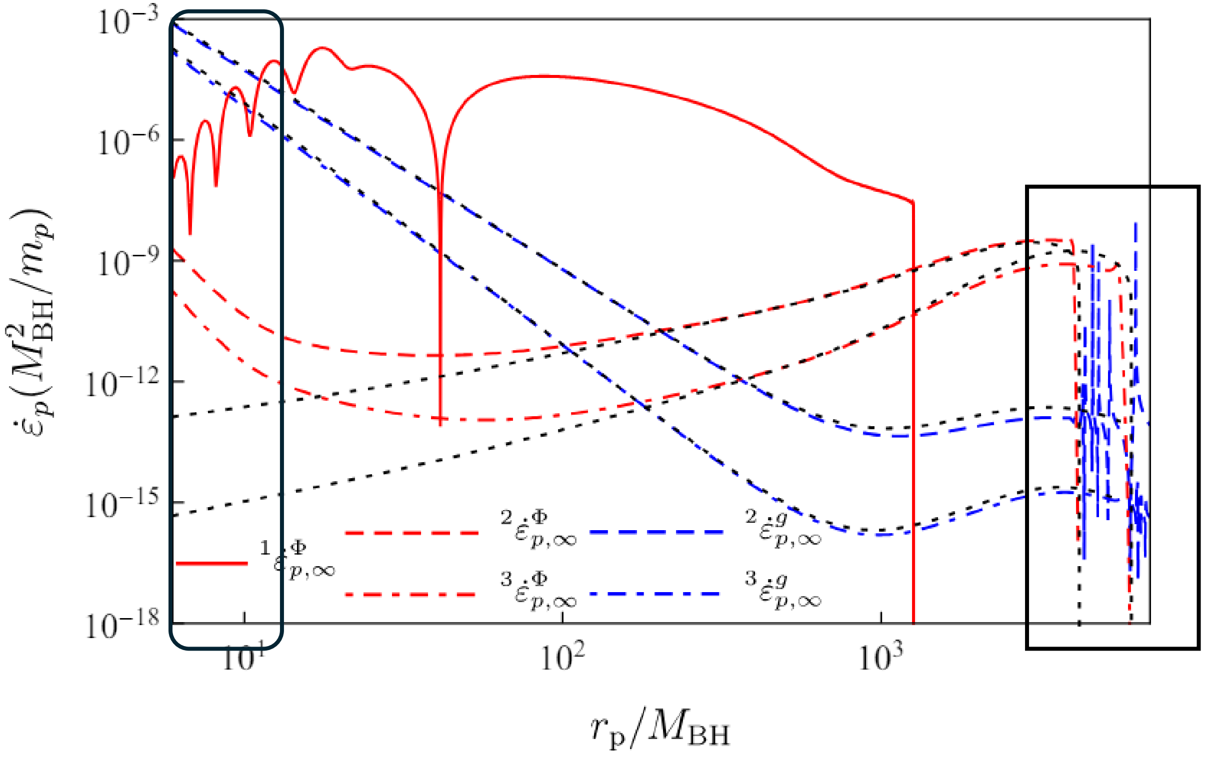
$$|\delta\phi_{\rm GW}| \sim \frac{5h}{16\nu^2}\frac{M\Delta\Omega_{\rm res}}{(M\Omega_{\rm res})^{10/3}}\frac{T_{\rm obs}}{M}$$

$$|\delta\phi_{\rm GW}| \approx 8.6\times 10^3 {\rm rads}\left[\frac{10^5 M_\odot}{M}\right]\left[\frac{T_{\rm obs}}{1{\rm yr}}\right]$$

$$\times\left[\frac{h/\nu^2}{10^{-2}}\right]\left[\frac{\sigma_I M}{10^{-5}}\right]\left[\frac{0.1}{\sigma_R M}\right]^{10/3}$$

EMRI: BH surrounded by (scalar) dark matter

Duque et al. arXiv:2312.06767 (2023)



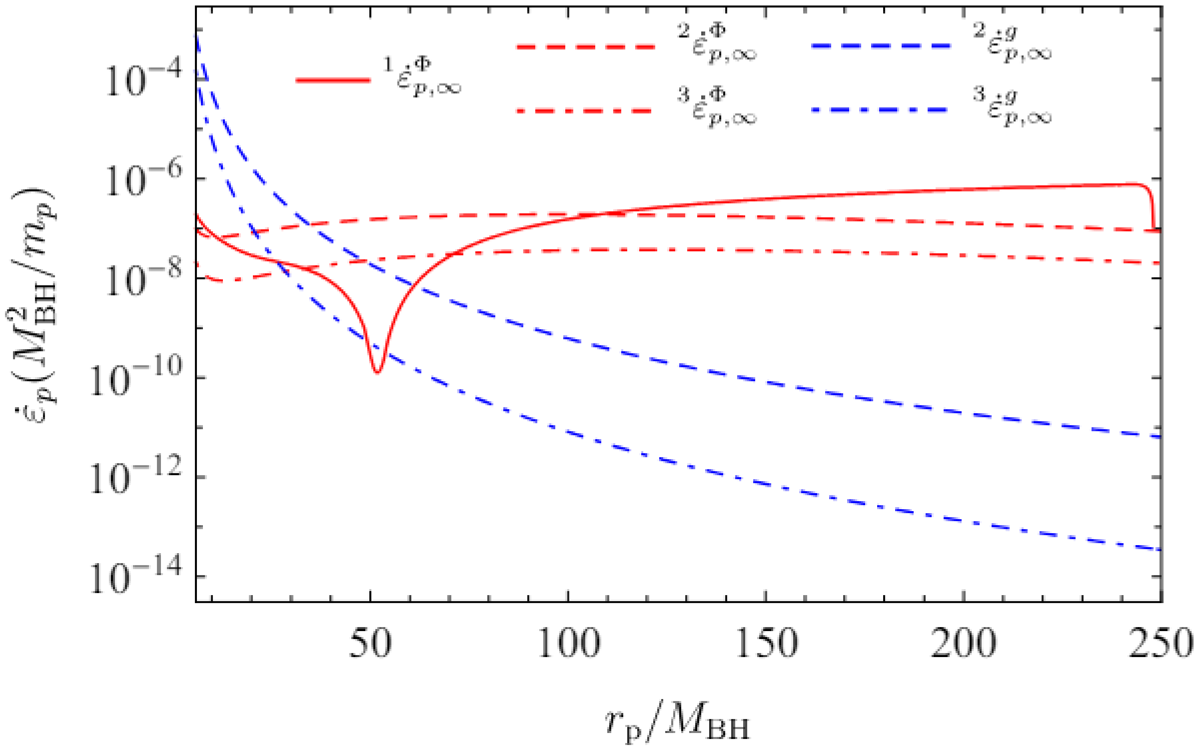
$$\frac{\dot{T}}{T} = \frac{3}{2}\,\frac{\textit{Energy Lost}}{\textit{Orbital energy}}.$$

For Sgr A* like scenarios

$$\delta_{\rm cyc} \sim \left(\frac{t_{\rm obs}}{t_\Phi}\right)\#_{\rm cyc} \gtrsim 200 \text{ cycles}$$

EMRI: BH surrounded by a cloud

Duque et al. arXiv:2312.06767 (2023). Brito, Shah Phys.Rev.D 108 8, 084019 (2023)



$$\delta_{\rm cyc} \sim 20\left(\frac{q}{10^{-5}}\right)\left(\frac{t_{\rm obs}}{4\,{\rm yr}}\right)\left(\frac{\Omega_{\rm p}/\pi}{0.3\,{\rm mHz}}\right)^{1/3}$$

Final remarks

- Binaries in environments can be remarkably different.
- Dynamical friction is important in eccentricity and CM boosts.
- Period shifts can be a discriminator.
- Axisymetric time-dependent environment introduces resonances.

Thank you!

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ON GRAVITY AND FIELDS

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02-06 DECEMBER 2024