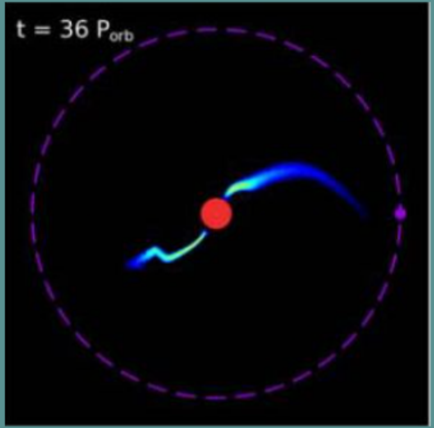
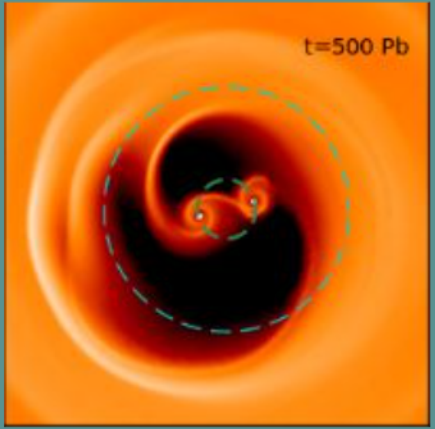
Electromagnetic signals From EMRIs and Massive Black Hole Binaries





In collaboration with: Matteo Bonetti, Alessandro Lupi, Giovanni Miniutti, Elisa Bortolas, Margherita Giustini, Massimo Dotti, Alberto Sesana, Riccardo Arcodia, Taeho Ryu

Alessandra Franchini

June 8th 2023

“Environmental effects on binary black holes”

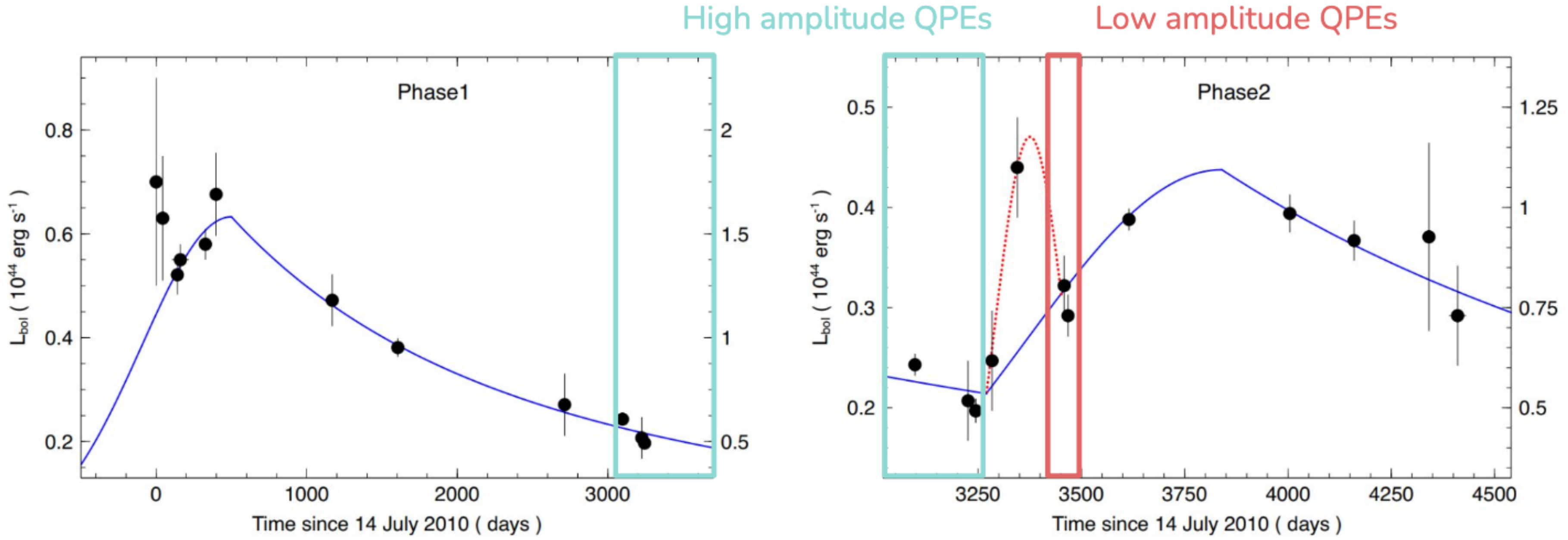
Quasi-Periodic Eruptions

Quasi-Periodic Eruptions (QPEs, Miniutti+19, Giustini+20, Arcodia+21,22) are **fast bursts in the soft X-ray band**, repeating every few hours, superimposed to an otherwise stable quiescent X-ray level that is consistent with emission from a radiatively efficient accretion flow around relatively low mass massive black holes (MBHs). During these bursts, the X-ray count rate increases by up to two orders of magnitude.

- **thermal-like X-ray spectra** with temperature evolving from kB*T~50-80 eV to ~100-250 eV
- **one to few hours** with a typical duty cycle of 10-30%
- peak X-ray luminosity is **~$10^{42\text{-}43}$ erg/s**
- observed with XMM-Newton, Chandra,Swift and eROSITA

QPEs in GSN 069

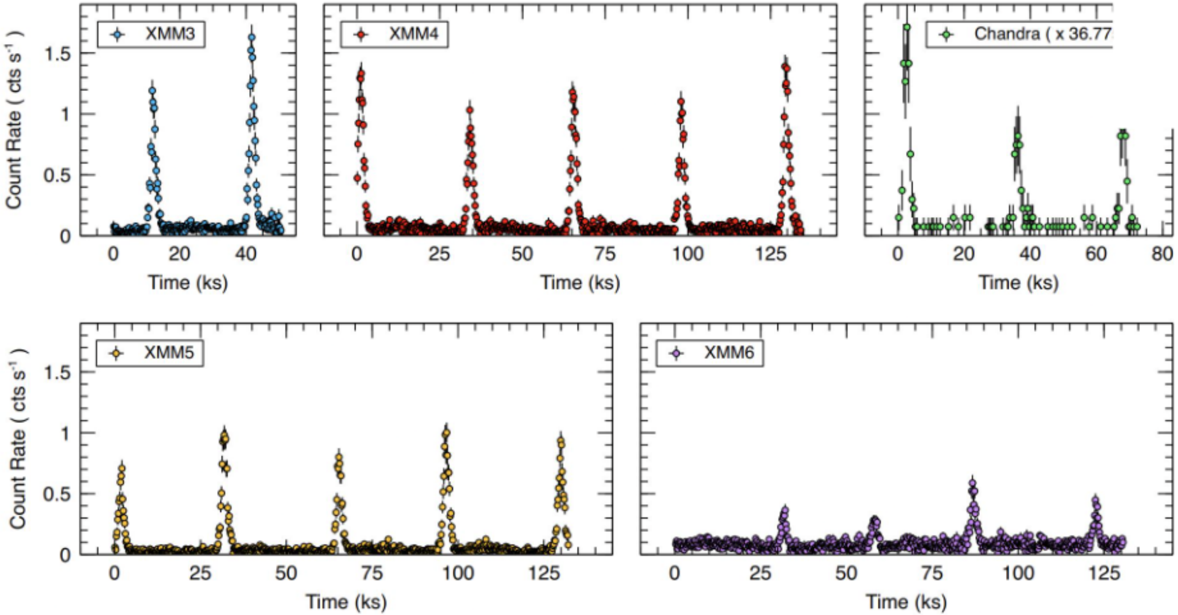
Miniutti et al., A&A 670, A93 (2023)

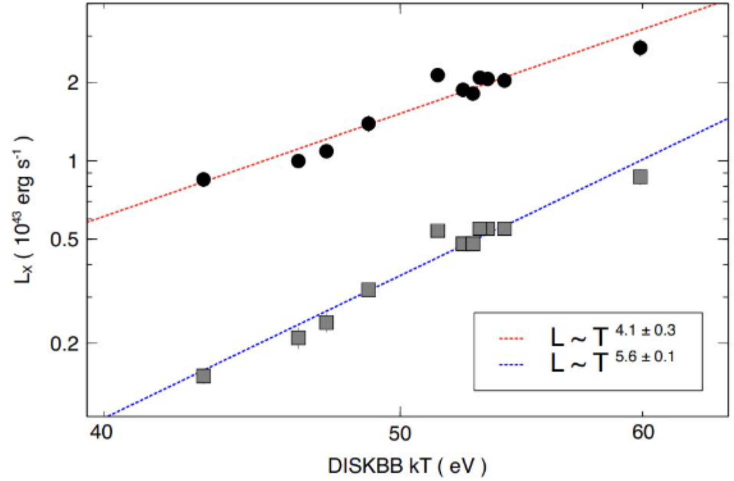


Bolometric luminosity decay consistent with both a total (n = -5/3) and partial (n = -9/4) disruption of a ~0.5 solar masses star

QPEs in GSN 069

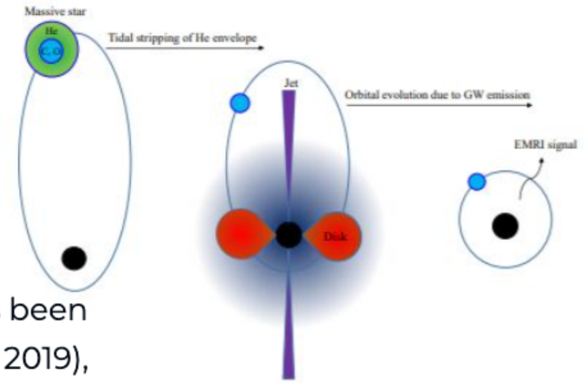
Miniutti et al., Nature, 573, 7774 (2019)





Bolometric correction is small in the range 0.2-2 keV (red line). This can be achieved only if the disc (formed from a TDE) is narrow as this would suppress the optical/UV emission.

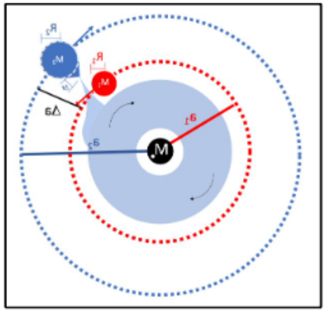
Models to explain QPEs



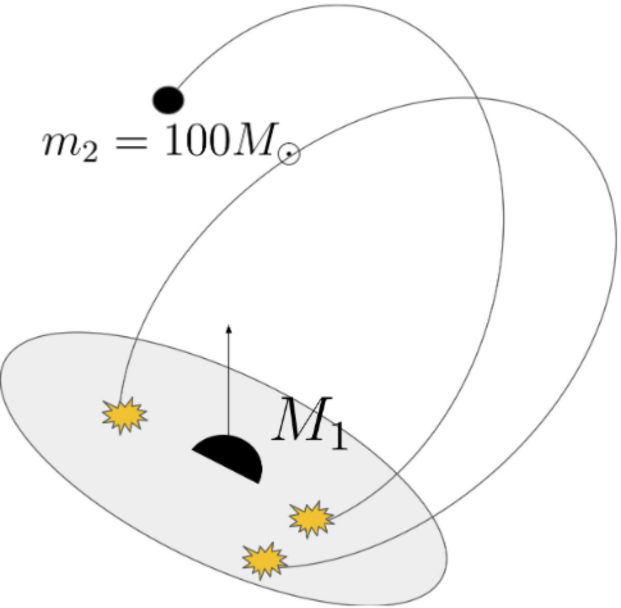
QPEs are an extreme, and still puzzling, X-ray variability phenomenon that has been recently detected from the nuclei of 4 nearby galaxies: GSN 069 (Miniutti et al. 2019), ERO-QPE1 (Arcodia et al. 2021), ERO-QPE2 (Arcodia et al. 2022) and RX J1309 (Giustini et al. 2020).

Several explanations have been proposed so far:

- Tidal stripping of the He envelope of a massive star (Wang+19)
- WDs on highly eccentric (e > 0.9) orbit filling up their Roche lobes and feeding the MBHs during their pericenter passages (King20, Chen+22, King22)
- Main sequence star undergoing stable or unstable mass transfer (Krolik+22, Linial+22)
- Multiple EMRIs interacting among them (Metzger+22)
- **Impacts of a much smaller mass companion in an accretion disc** (Xian+21, Linial+23, Tagawa+23, **Franchini+23**)



Impacts in an accretion disc: ingredients



- Post-Newtonian evolution to model relative motion (3.5 PN + leading order spin-orbit, see Blanchet 2014)

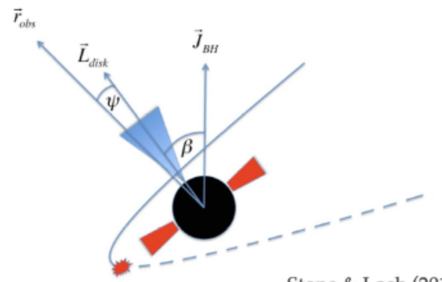
$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{GM}{r^2}\left(\left(1+\mathcal{A}\right)\,\mathbf{n} + \mathcal{B}\mathbf{v}\right) + \mathbf{C}_{1.5} + \mathcal{O}\left(\frac{1}{c^8}\right),$$

- Rigidly precessing disc around the primary due to Lense-Thirring (Franchini+16)

$$\Omega_p = \frac{\int_{R_{\rm ISCO}}^{R_{\rm out}} \Omega_{\rm LT}(R)L(R)2\pi R dR}{\int_{R_{\rm ISCO}}^{R_{\rm out}} L(R)2\pi R dR}$$

Franchini A., Bonetti M. et al. A&A in press, (2023)

Rigid Lense-Thirring precession



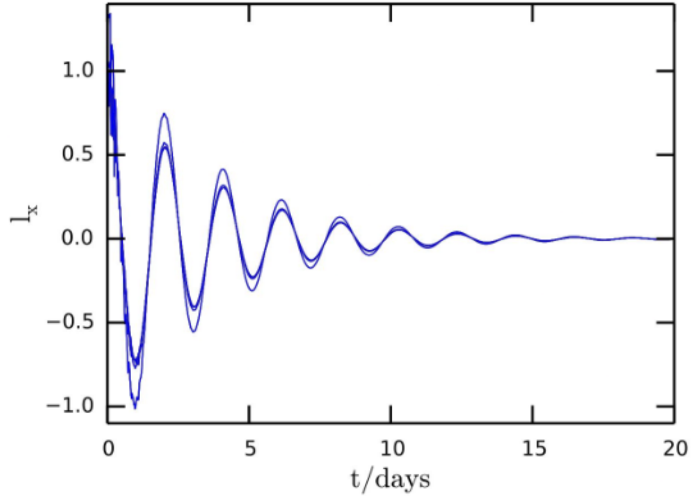
Stone & Loeb (2014)

Bending wave equations for the warp propagation inside a thick disc ($H/R \gtrsim \alpha$)

$$\Sigma R^3 \Omega \frac{\partial \mathbf{l}}{\partial t} = \frac{\partial \mathbf{G}}{\partial R} + \mathbf{T}$$

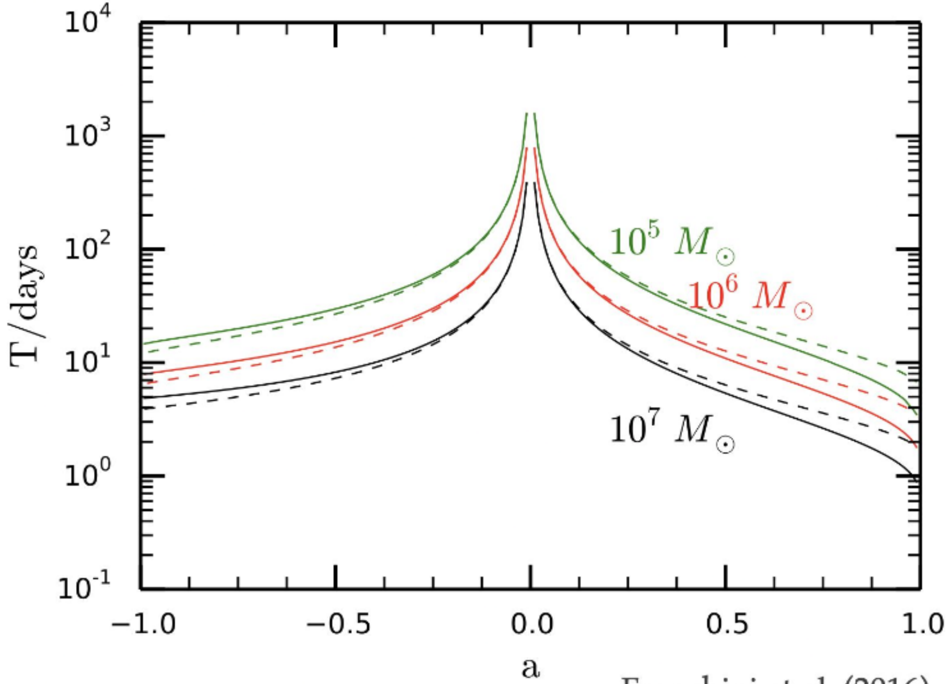
$$\frac{\partial \mathbf{G}}{\partial t} + \left(\frac{\kappa^2 - \Omega^2}{\Omega^2}\right)\frac{\Omega}{2}\mathbf{e_z} \times \mathbf{G} + \alpha \Omega \mathbf{G} = \Sigma R^3 \Omega \frac{c_s^2}{4}\frac{\partial \mathbf{l}}{\partial R}$$

$$\mathbf{T} = -\Sigma R^2 \Omega \left(\frac{\Omega_z^2 - \Omega^2}{\Omega^2}\right)\frac{\Omega}{2}\mathbf{e_z} \times \mathbf{l}\,.$$



If the disc is narrow and thick enough it can precess as a rigid body around the central BH.

Disc precession periods



Franchini et al. (2016)

QPE sources typically have masses between 10^5 and 10^6 M_{sun} and therefore the disc precession periods are

$$T \simeq 1 - 100\text{days}$$

We take the disc mass to be 0.01-4 M_{sun} and to be distributed with a power law profile from the Innermost Stable Circular Orbit to ~ 300 R_g

Emission mechanism

Large enough to produce the observed luminosities for prograde orbits and low inclinations (i.e. low relative velocities)

Optically thick gas cloud pulled out of the disc during the crossings.

The cloud expands emitting black-body radiation.

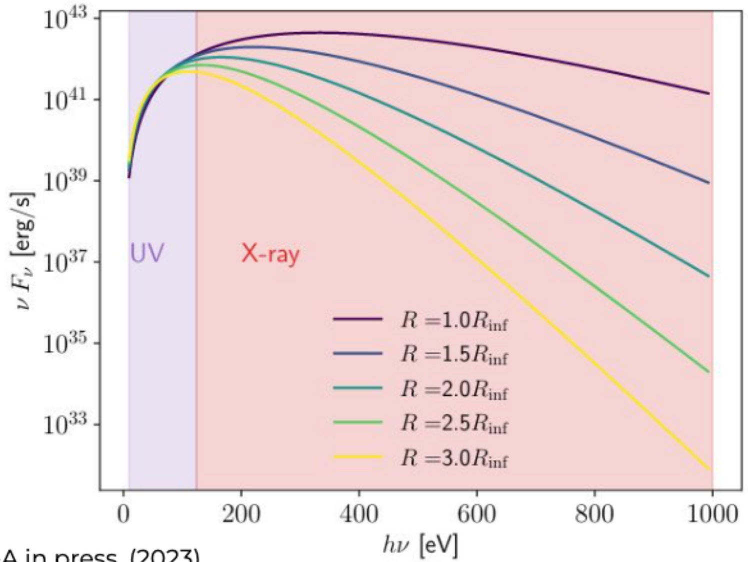
Initial radius of the cloud (~ 10^{11} cm)

$$R_{\rm in} \sim R_{\rm inf} = \frac{GM_2}{c_{\rm s}^2 + v_{\rm rel}^2}$$

$$R(t) = R_{\rm in} + \frac{2R_{\rm in}}{\Delta t_{\rm QPE}} t$$

Post-shock temperature in a radiation pressure dominated gas

$$T_2 = \left[1 + \frac{8}{7}\left(\mathcal{M}_{\rm e,1}^2 - 1\right)\right]^{1/4} T_1$$



Franchini A., Bonetti M. et al. A&A in press, (2023)

Emission mechanism

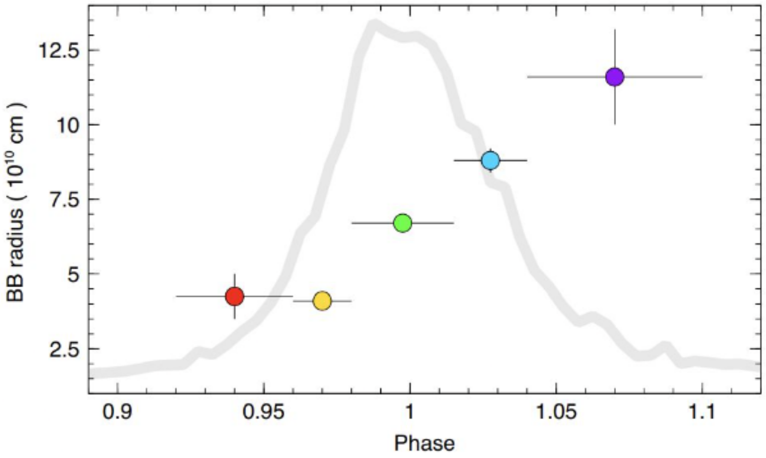
Optically thick gas cloud pulled out of the disc during the crossings.

The cloud expands emitting black-body radiation.

$$L_X = 4\pi R(t)^2 \int_{0.2\mathrm{keV}}^{2\mathrm{keV}} \frac{2h\nu^3}{c^2} \frac{d\nu}{e^{h\nu/k_B T_{\rm exp}} - 1}$$

$$T_{\rm exp} = T_2(R_{\rm in}/R(t))$$

Post-shock temperature of the gas (~10^6 K). Cloud temperature decreases below the quiescence level as the cloud expands by a factor 3



Franchini A., Bonetti M. et al. A&A in press, (2023)

The nature of the EMRI companion

Only impacts that form clouds with initial size **R_{in} ~ 10^{11} cm** are able to reproduce the observed luminosities.

- Neutron stars and White Dwarfs are excluded from our model
- BHs with masses << 100 M_{sun} never reach the required R_{in}
- BHs with masses >> 100 M_{sun} have a short GW inspiral time
- Stars get tidally disrupted. For at least two sources the pericentre is < R_t
- In three out of four sources the star would overfill its Roche-Lobe

Franchini A., Bonetti M. et al. A&A in press, (2023)

Light curves - “more regular” sources

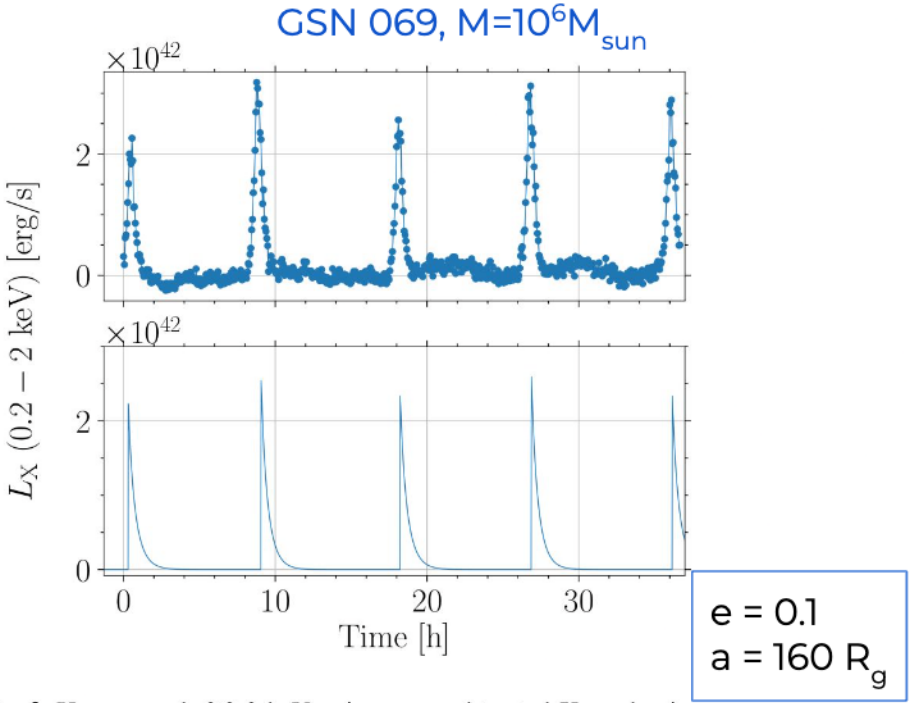


Fig. 3. Upper panel: 0.2-2 keV quiescence-subtracted X-ray luminosity light curve from the *XMM-Newton* observation XMM5 of GSN 069 (Miniutti et al. 2023). Lower panel: synthetic light curve obtained with the parameters listed in Sect. 3.1.1.

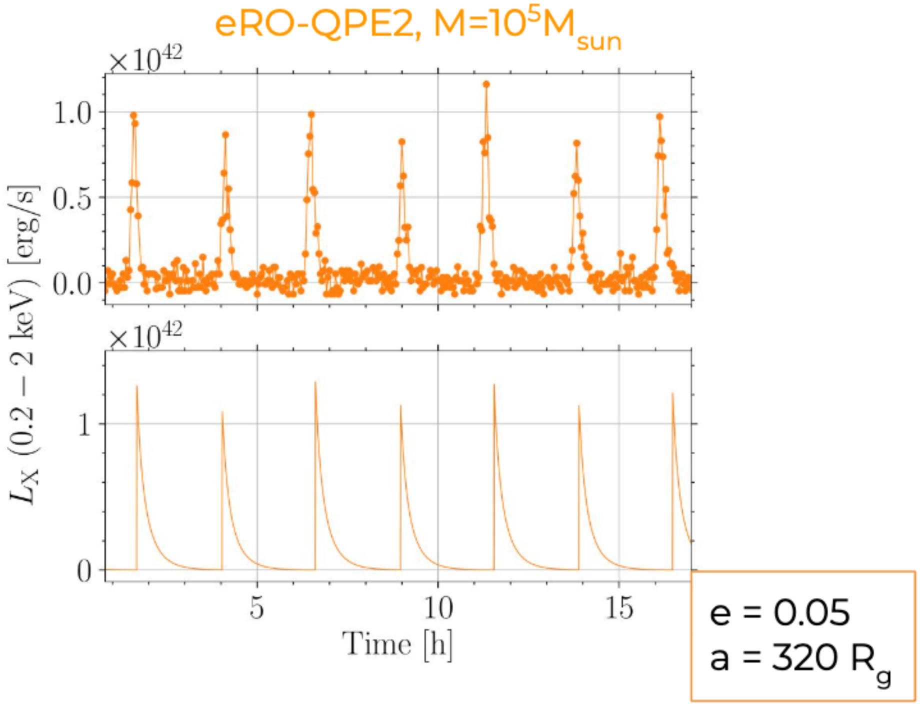
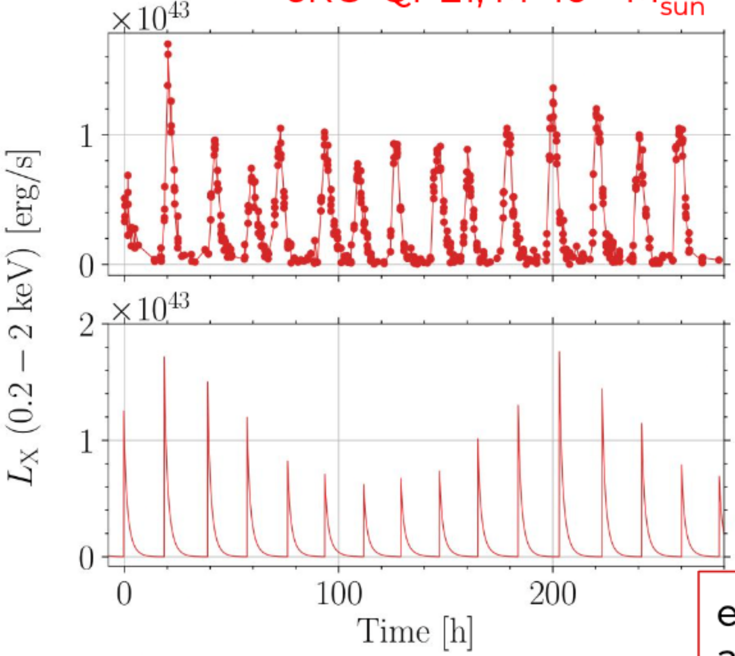


Fig. 4. Upper panel: 0.2-2 keV quiescence-subtracted X-ray luminosity light curve from one of the *XMM-Newton* observations of eRO-QPE2. Lower panel: synthetic light curve obtained with the parameters listed in Sect. 3.1.2.

Franchini A., Bonetti M. et al. A&A in press, (2023)

Light curves - “irregular” sources

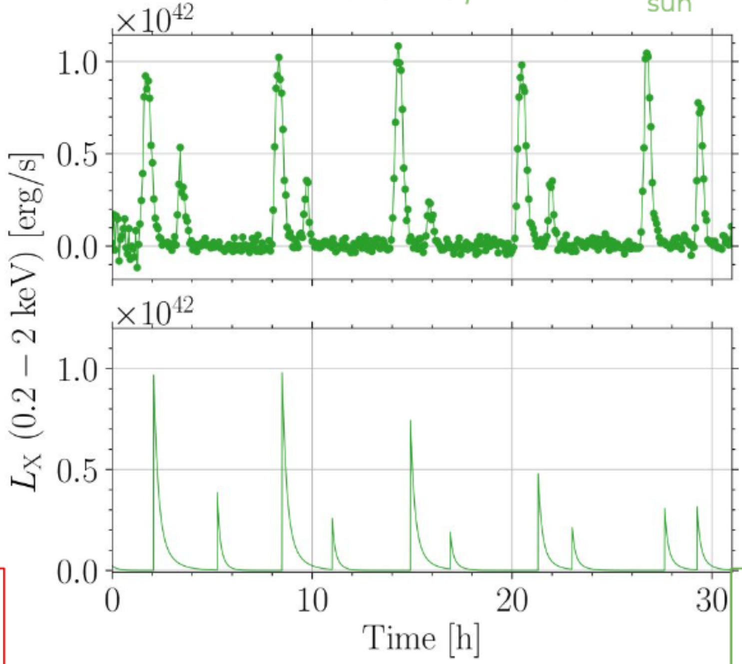
eRO-QPE1, M=$10^{5.8}$M$_{sun}$



e = 0.05
a = 355 R_g

Fig. 5. Upper panel: 0.2-2 keV X-ray luminosity light curve from a *NICER* ~ 250 hr-long monitoring of eRO-QPE1. The quiescent level is undetected by *NICER*. Lower panel: synthetic light curve obtained with the parameters listed in Sect. 3.1.3.

RX J1301.9, M=$10^{6.3}$M$_{sun}$



e = 0.4
a = 50 R_g

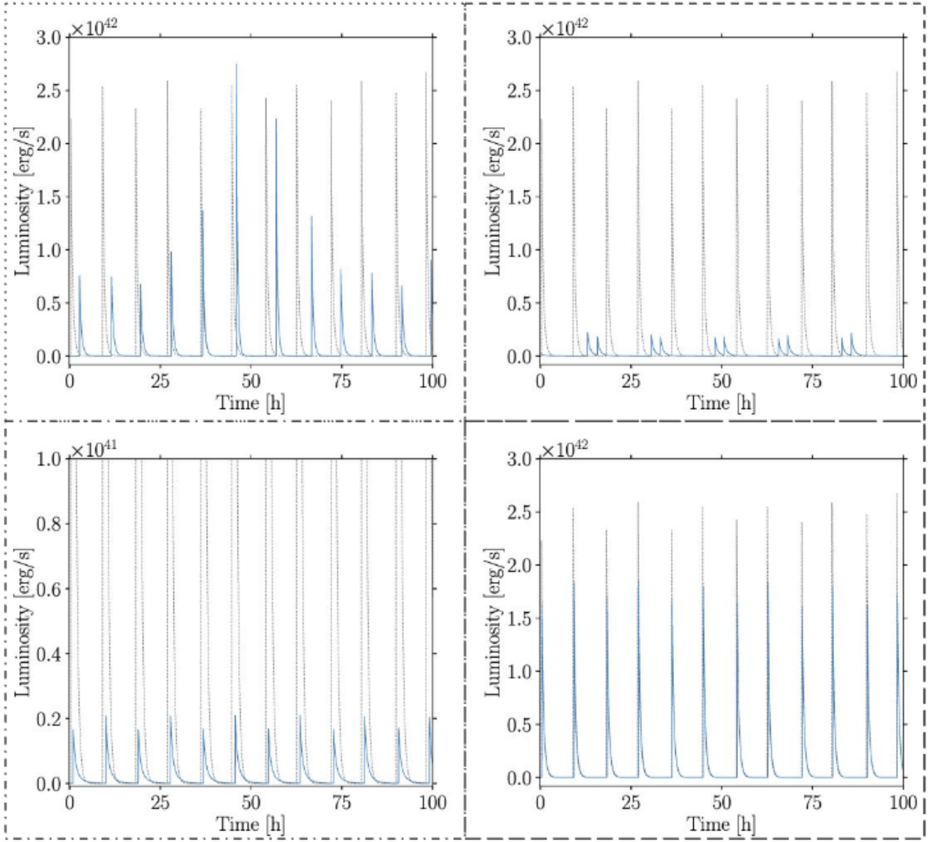
Fig. 6. Upper panel: 0.2-2 keV quiescence-subtracted X-ray luminosity from one of the *XMM-Newton* observations of RX J1301.9+2747. Lower panel: synthetic light curve obtained with the parameters listed in Sect. 3.1.4.

Franchini A., Bonetti M. et al. A&A in press, (2023)

Effect of orbital and disc parameters

Higher MBH spin

Higher EMRI eccentricity

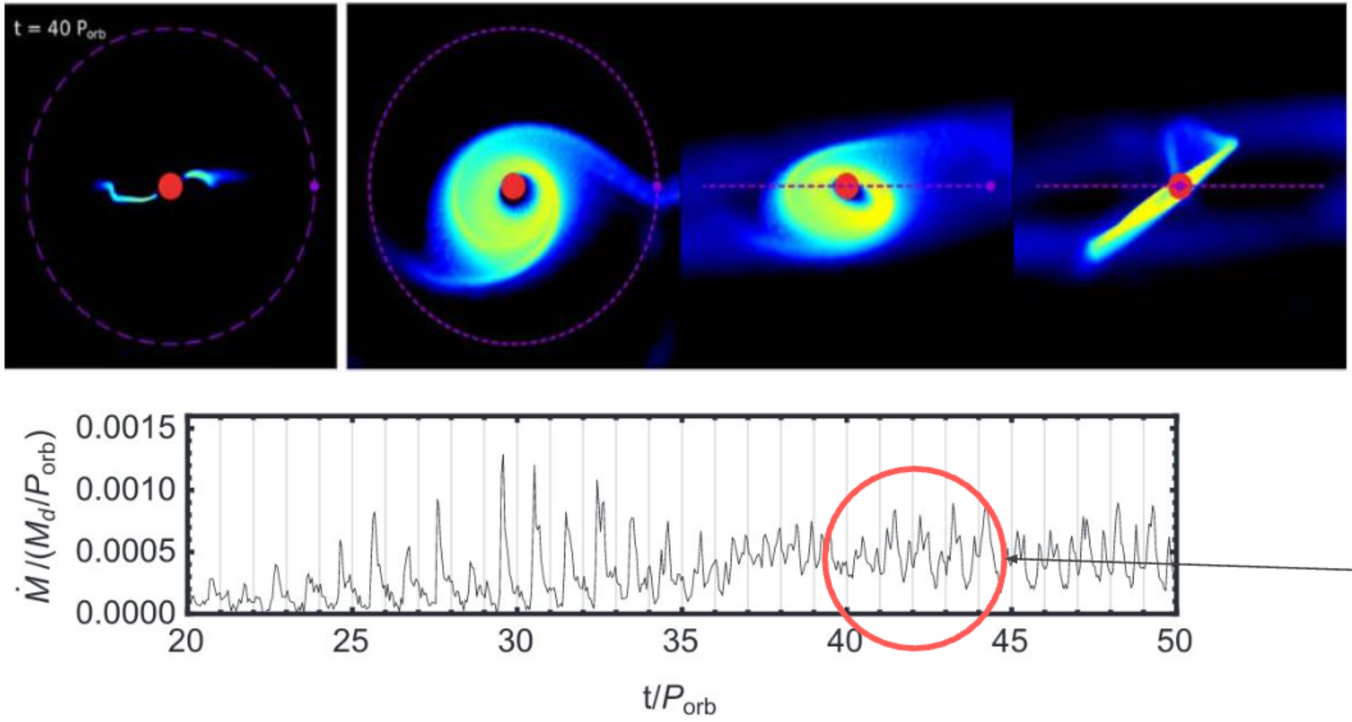


Retrograde EMRI

No disc precession

Hydrodynamical view

Martin & Franchini, ApJL, 992, L37 (2021)

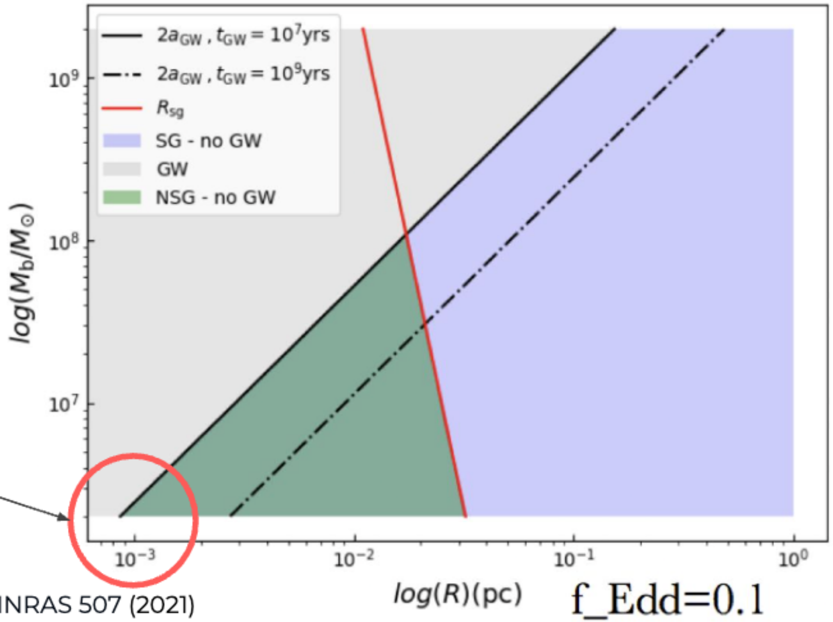


The combination of apsidal and nodal precession of the disc gives rise to up to three outbursts per orbit

Massive Black Hole Binaries in gaseous environment

After a successful (?) dynamical friction driven inspiral, bound binaries in the central pc of galaxies do evolve through the interaction with gas before diving into the GW driven phase.

LISA binaries evolve within gaseous discs where the gas self-gravity can be neglected

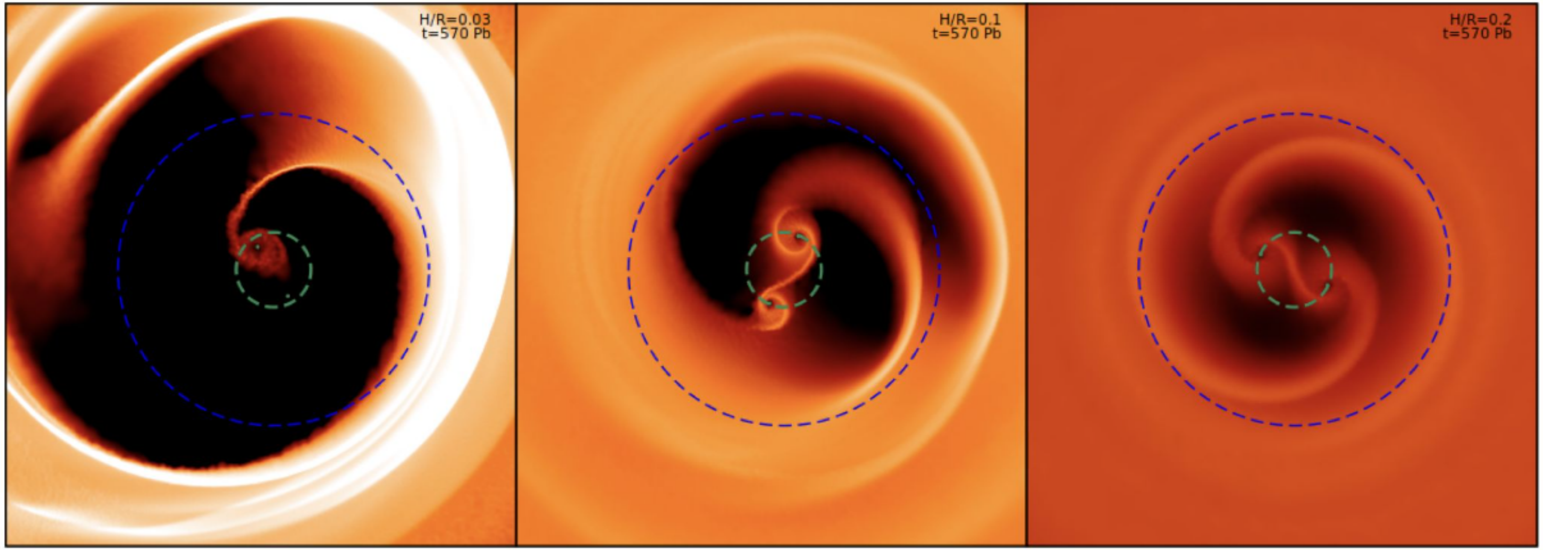


Franchini A., Sesana A. & Dotti M., MNRAS 507 (2021)

Newtonian binary-disc interactions

Franchini A., Lupi A. & Sesana A., ApJL 929 L13. (2022)
Franchini A., Lupi A., Sesana A. , Haiman Z., MNRAS 552 (2023)

We used 3D hyper-lagrangian resolution numerical simulations to investigate the interaction between a binary and an isothermal circumbinary disc



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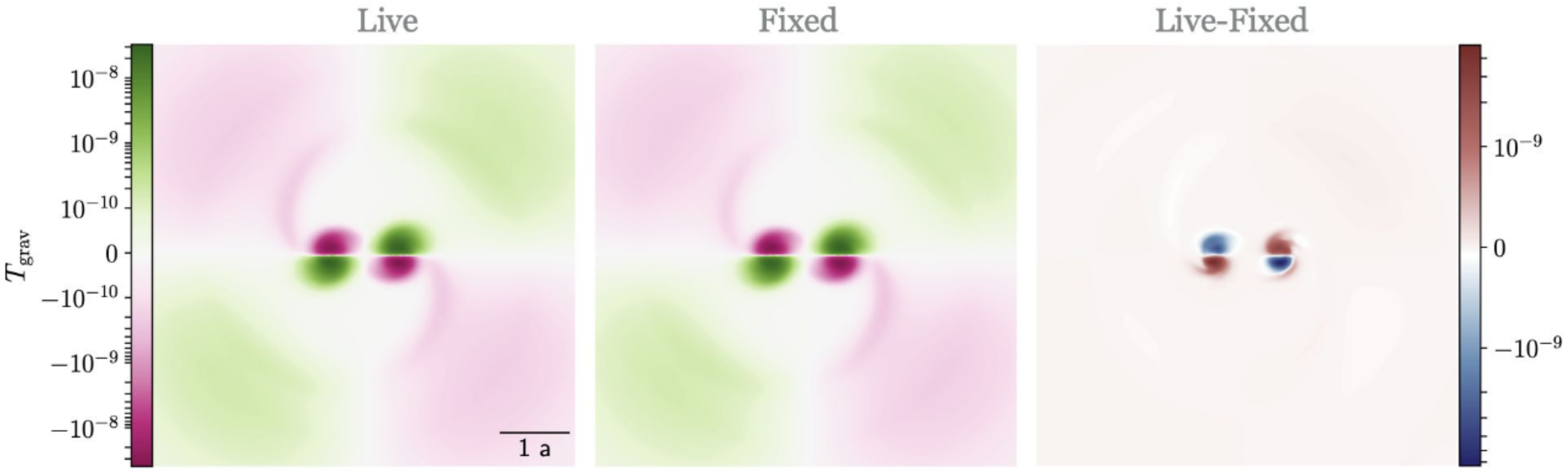

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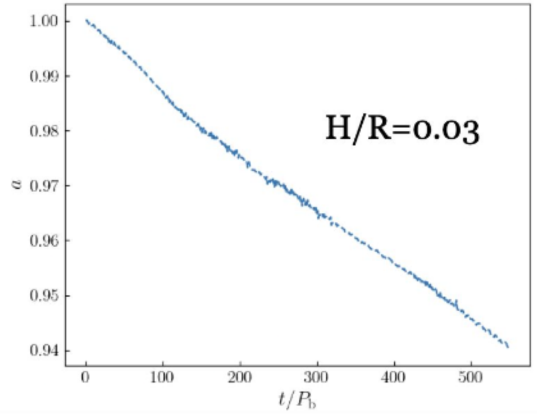
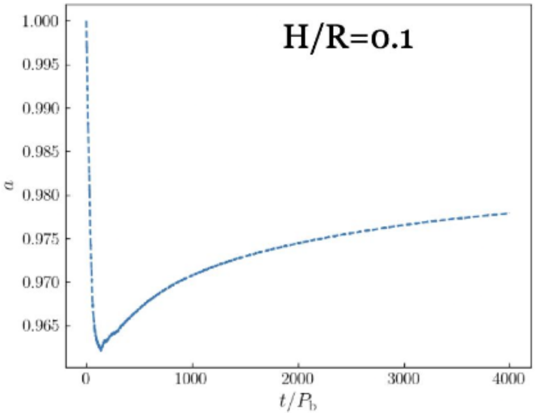
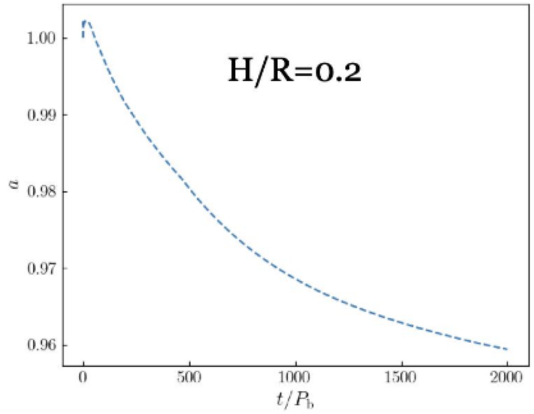






- Circumbinary discs drive the binary to harden, except for a very narrow region of the parameter space
- Viscous processes in the disc are fundamental for the balance between positive and negative torques

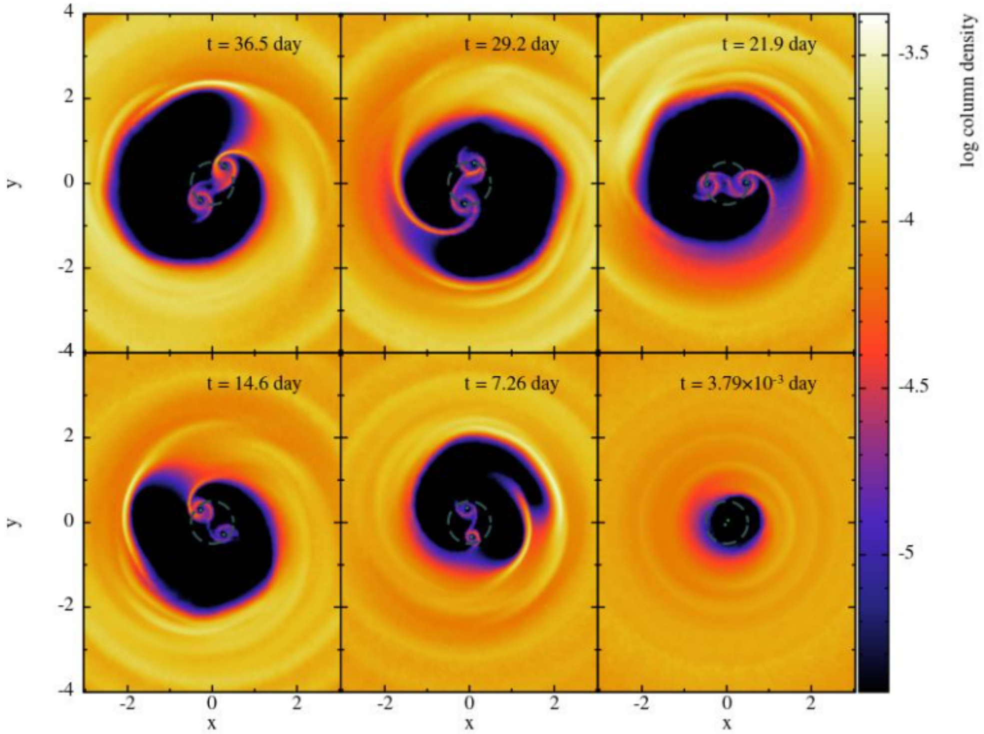
PN binary-disc interactions

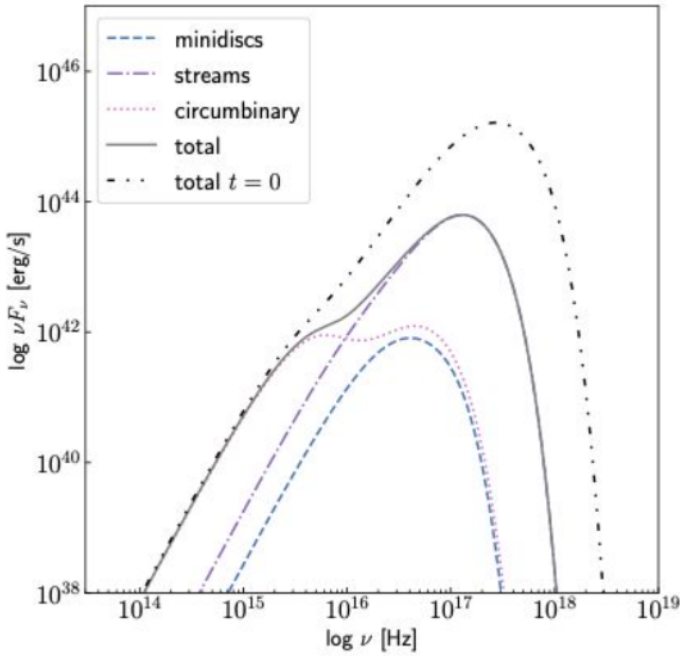
PRELIMINARY

Franchini A., Bonetti M., Lupi A. & Sesana A.. (in prep.)

$a = 60\ R_g,\ e = 0,\ M = 10^6 M_{sun}$

H/R=0.1





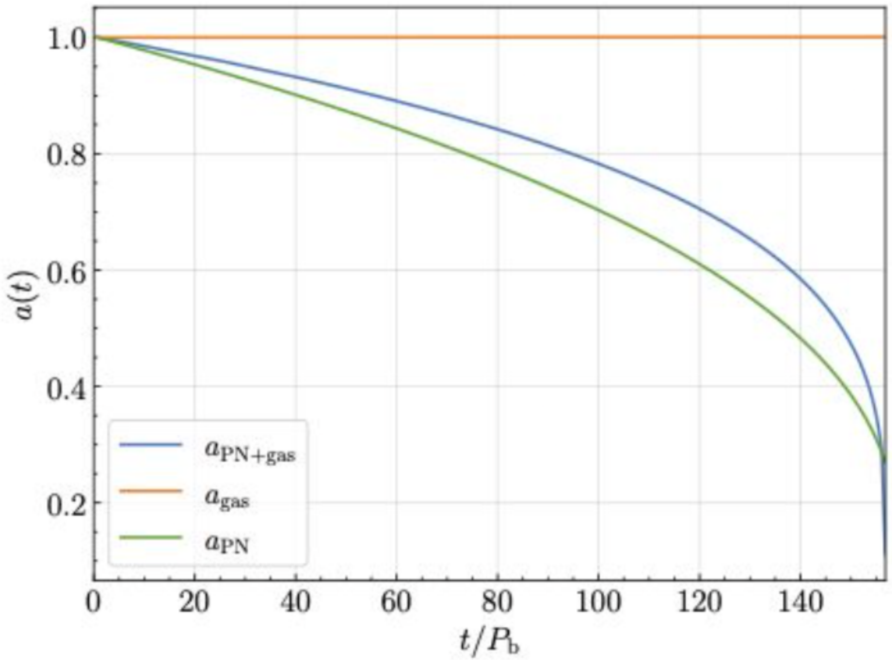
PRELIMINARY

PN binary-disc interactions

Franchini A., Bonetti M., Lupi A. & Sesana A.. (in prep.)

$a = 60\ R_g$, $e = 0$, $M = 10^6 M_{sun}$

H/R=0.1



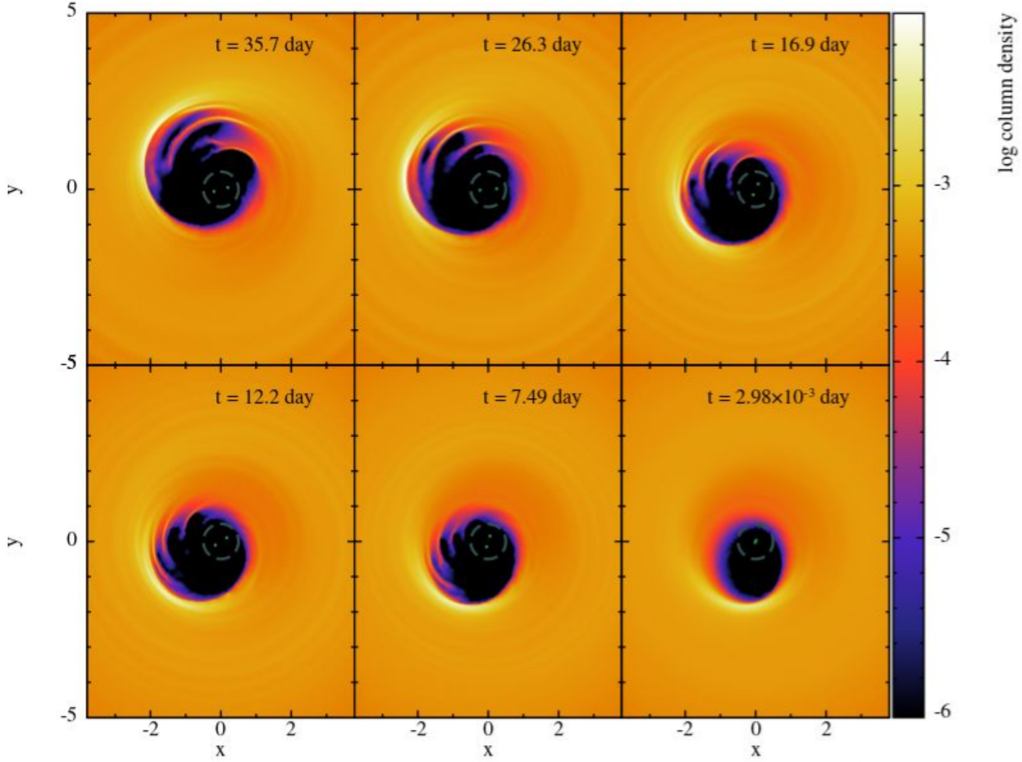
PRELIMINARY

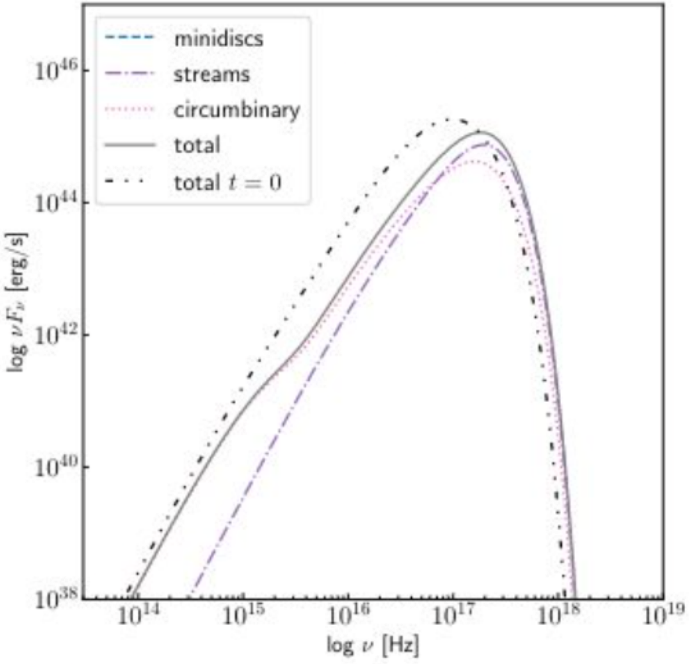
PN binary-disc interactions

Franchini A., Bonetti M., Lupi A. & Sesana A.. (in prep.)

a = 120 R_g, e = 0, M = $10^6 M_{sun}$

H/R=0.03





Conclusions on EMRIs

- We propose a model to explain QPEs invoking a 100Msun EMRI companion that crosses a rigidly precessing disc on a prograde orbit with low inclination with respect to the disc.
- The combination of the apsidal and nodal precession frequency of the EMRI and the nodal precession frequency of the disc reproduce the observed variety of QPE periodicities.
- The emission is generated by an optically thick cloud of gas that is pulled out from the disc and adiabatically expands, emitting as a black body. The luminosity decline is due to the cloud expansion
- If this model can actually explain all the detected QPEs it will have important consequences on the characterisation of the EMRI population
- We plan on extending our analytical work using hydro simulations with PN corrections.

Conclusions on MBHBs

- The binary semi-major axis decreases with time as a result of its interaction with a circumbinary disc in a vast region of the parameter space
- Including proper disc temperature evolution will shed light on the outcome of binary-disc interactions

- PN corrections to the binary dynamics allow us to study the possible EM signatures of MBHBs towards merger
- We are investigating the effect of a possible kick to the remnant MBH on the gas dynamics