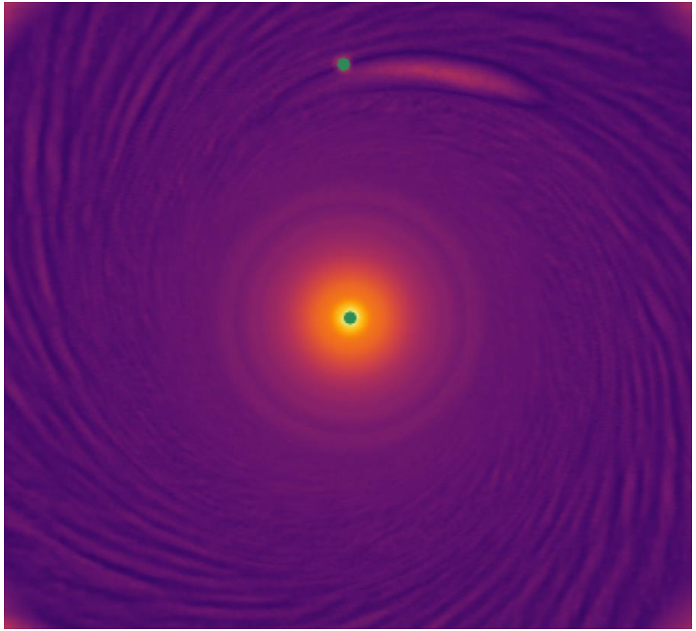


Can QPEs shed light on TDEs?

Alessia Franchini

in collaboration with Matteo Bonetti, Alessandro Lupi, Giovanni Miniutti et al.

Universität Zürich UZH

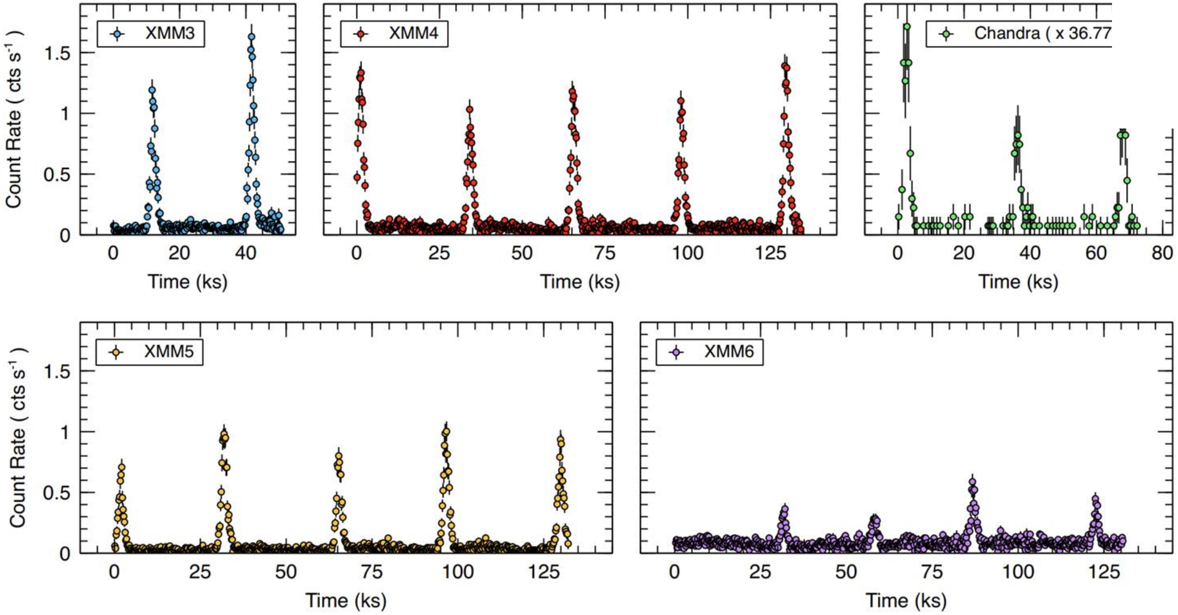
Quasi-Periodic Eruptions properties

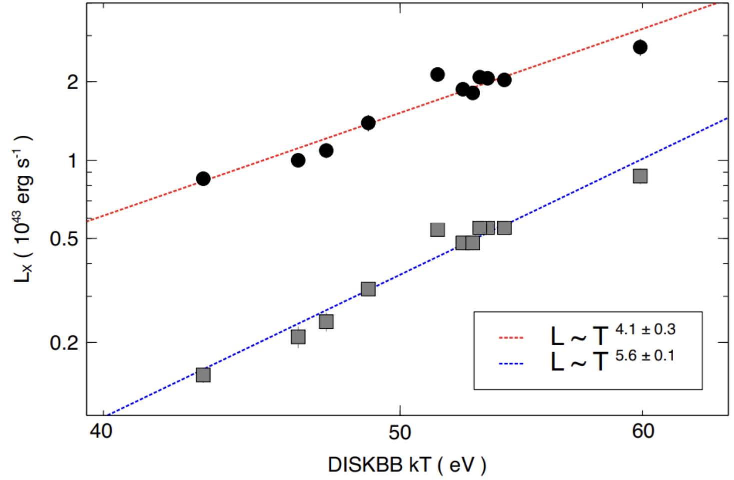
Quasi-Periodic Eruptions (QPEs, Miniutti+19,23, Giustini+20, Arcodia+21,22,24) are **fast bursts in the soft X-ray band**, repeating every few hours, superimposed to an otherwise **stable quiescent X-ray level that is consistent with emission from a radiatively efficient accretion** flow around relatively 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^{42-43} erg/s**
- observed with XMM-Newton, Chandra,Swift, NICER and eROSITA

QPEs in GSN 069

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





Bolometric correction is small in the range 0.2-2 keV (red line)

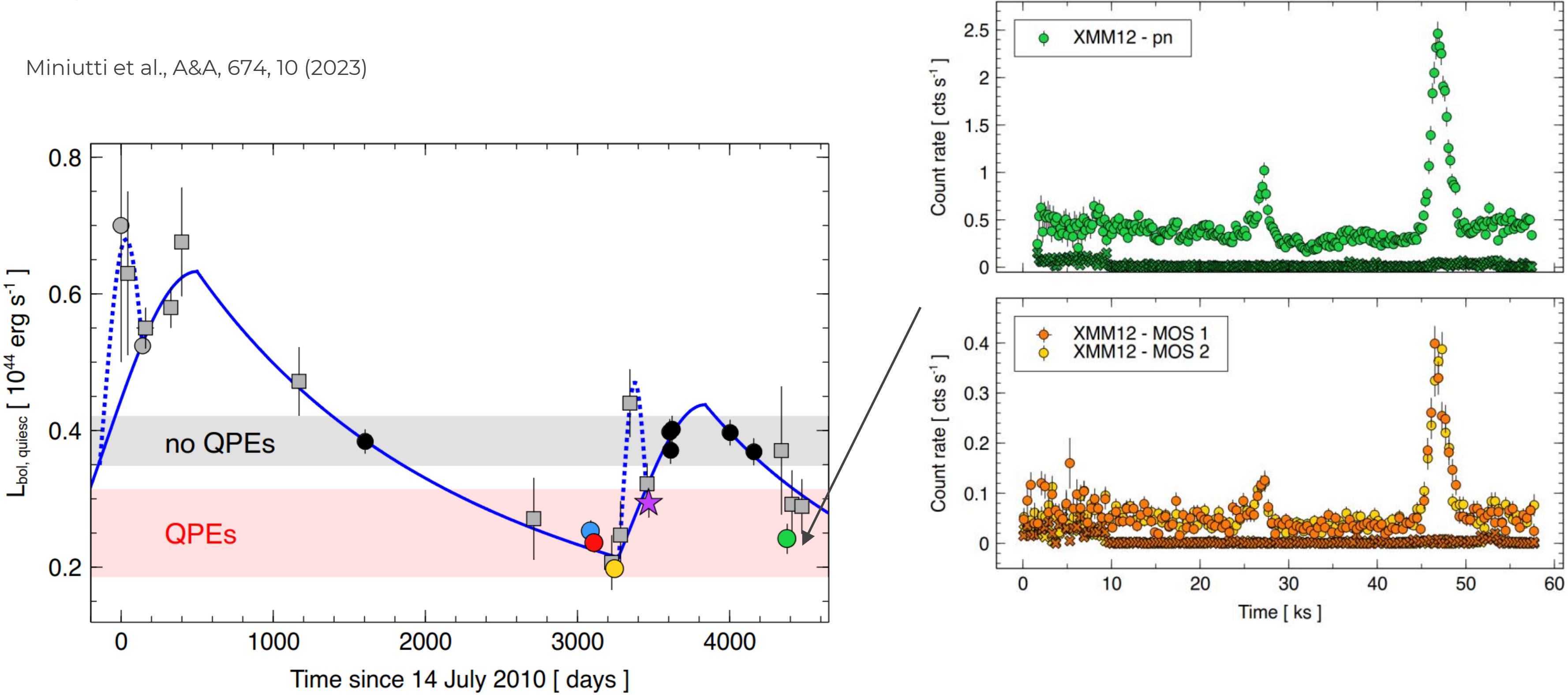
↓

disc is narrow as this would suppress the optical/UV emission

TDE disc?

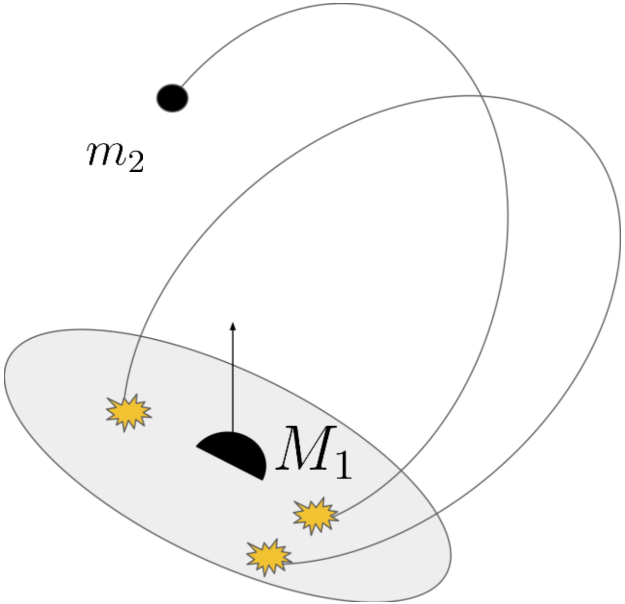
QPEs in GSN 069

Miniutti et al., A&A, 674, 10 (2023)



EMRI-disc impacts

Xian et al. (2021)
Linial & Metzger (2023)
Franchini et al. (2023)
Tagawa & Haiman (2023)



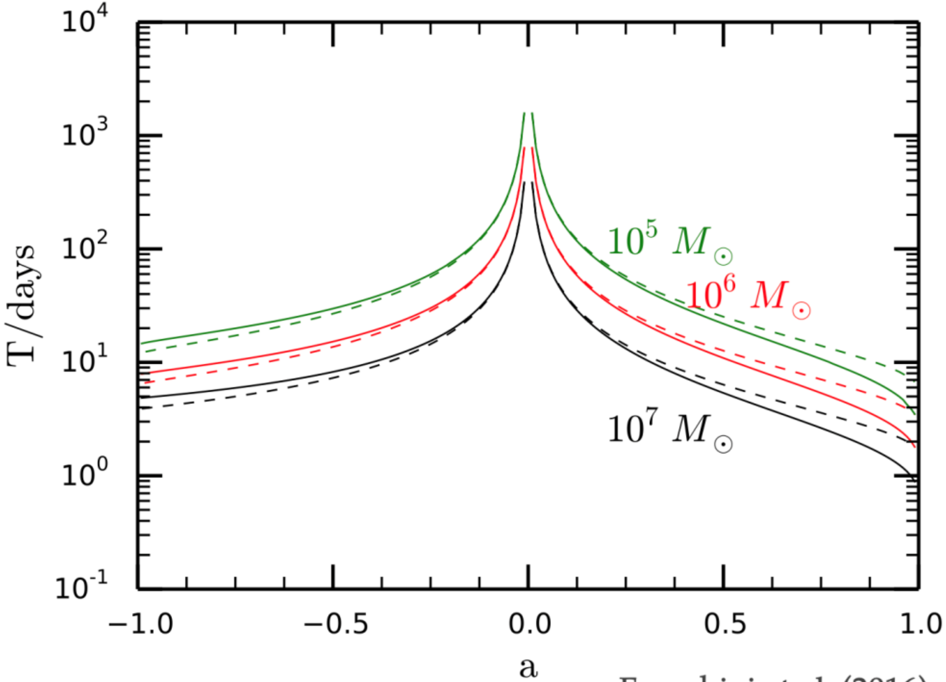
- Post-Newtonian evolution of the EMRI (3.5 PN + leading order spin-orbit, see Blanchet 2014)

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

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

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

Misaligned disc nodal precession periods



Franchini et al. (2016)

For a MBH with 10^6 M_{sun}, the TDE-like disc precession periods are

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

The **impact** between the precessing disc and the EMRI produces **Quasi Periodic Eruptions**

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 (Pihajoki 2016, Linial&Metzger 2023).

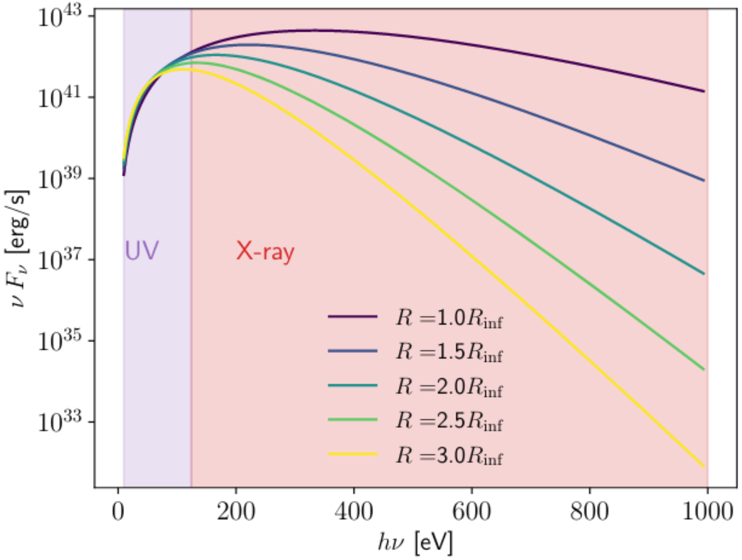
Initial radius of the cloud (~ 10^{11} cm)

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

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

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 675 A100, (2023)

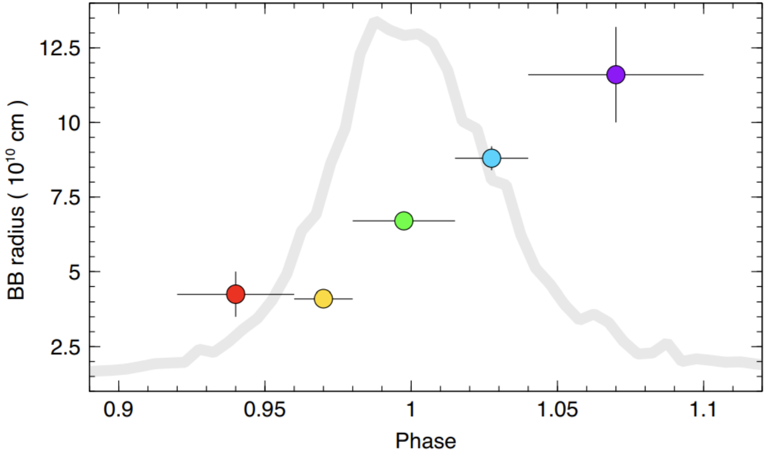
Franchini A., Bonetti M. et al. A&A 675 A100, (2023)

Emission mechanism

The cloud expands adiabatically, emitting black-body radiation.

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

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



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

On 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.

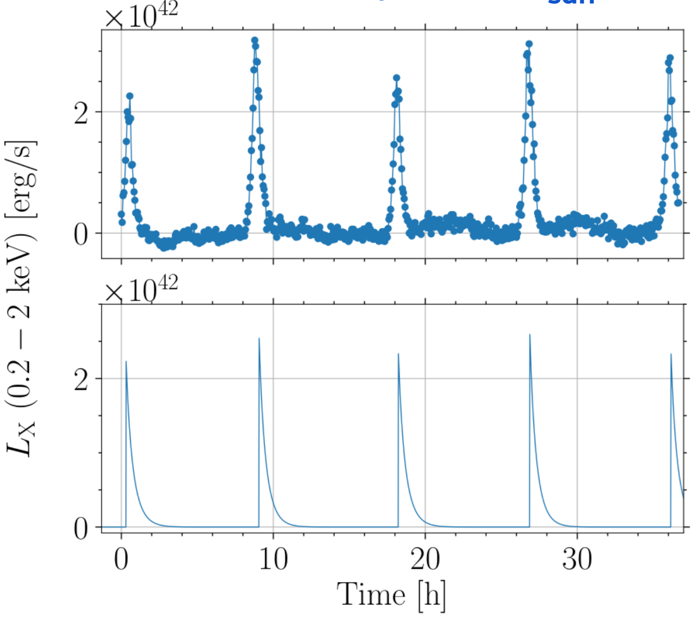
- Neutron stars and White Dwarfs are excluded from our model
- Small BH masses never reach the required cloud initial size
- BHs with masses > 100 M_{sun} have a short GW inspiral time
- Stars get tidally disrupted. **For at least two sources the pericentre is very close to the tidal radius**
- **In three out of four sources the star would overfill its Roche-Lobe**
- Stellar radius independent on the relative velocity, harder to reproduce different amplitude QPEs

→ BH companion with mass ~ few tens of solar masses

Franchini A., Bonetti M. et al. A&A 675 A100, (2023)

Light curves of the more regular sources

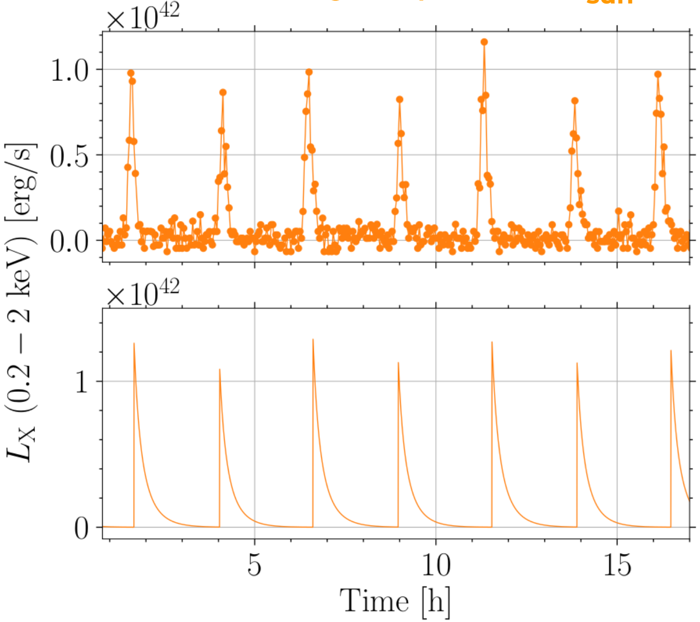
GSN 069, $M=10^6 M_{sun}$



e = 0.1
a = 160 R_g

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.

eRO-QPE2, $M=10^5 M_{sun}$



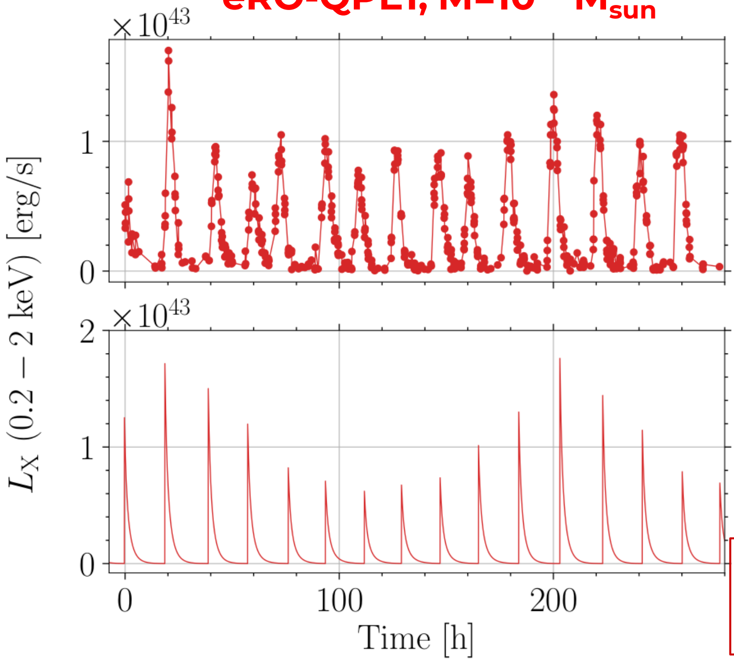
e = 0.05
a = 320 R_g

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 675 A100, (2023)
Chakraborty et al. ApJ 965 (2024)

Light curves of the more irregular sources

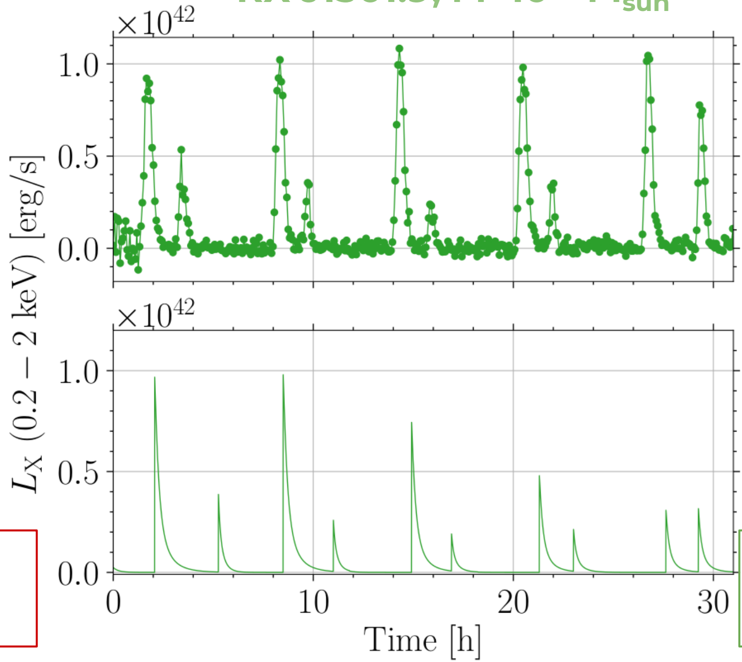
eRO-QPE1, $M=10^{5.8}M_{sun}$



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.

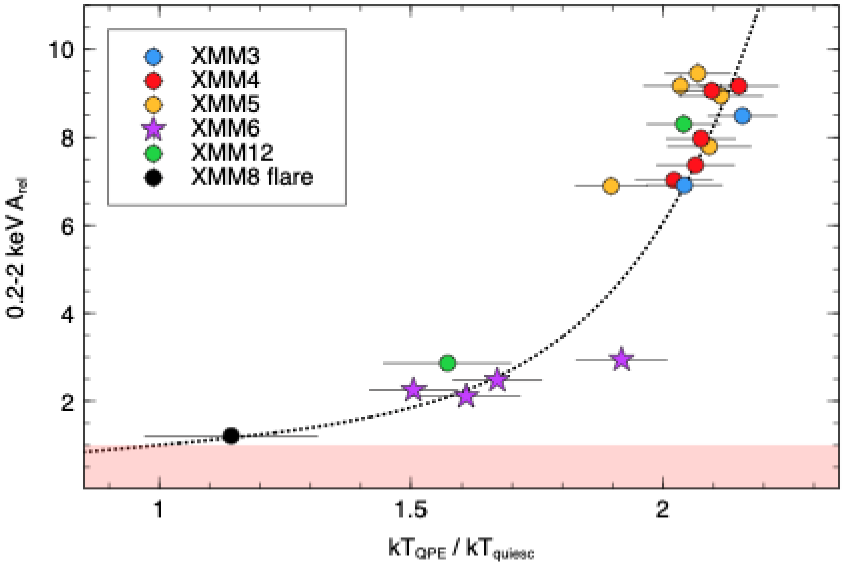
RX J1301.9, $M=10^{6.3}M_{sun}$

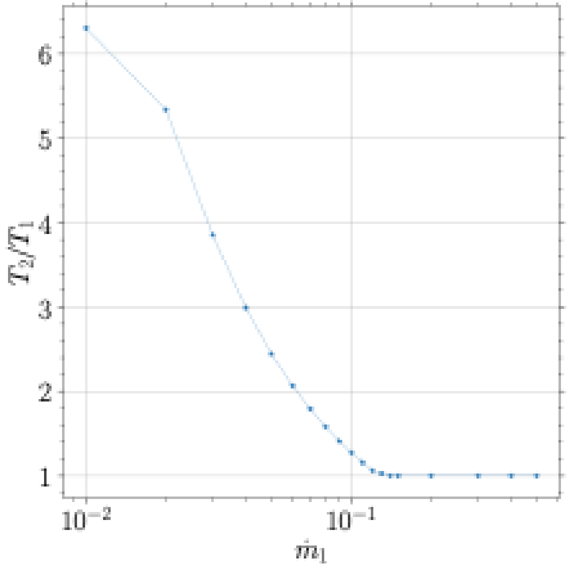


e = 0.4
a = 50 R_g

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.

QPE disappearance





$$T_{\rm QPE}/T_{\rm quiesc} \to 1$$

for increasing accretion rate onto the primary MBH, **consistent with the QPE disappearance at high Eddington fraction**

Franchini A., Bonetti M. et al. A&A 675 A100, (2023)

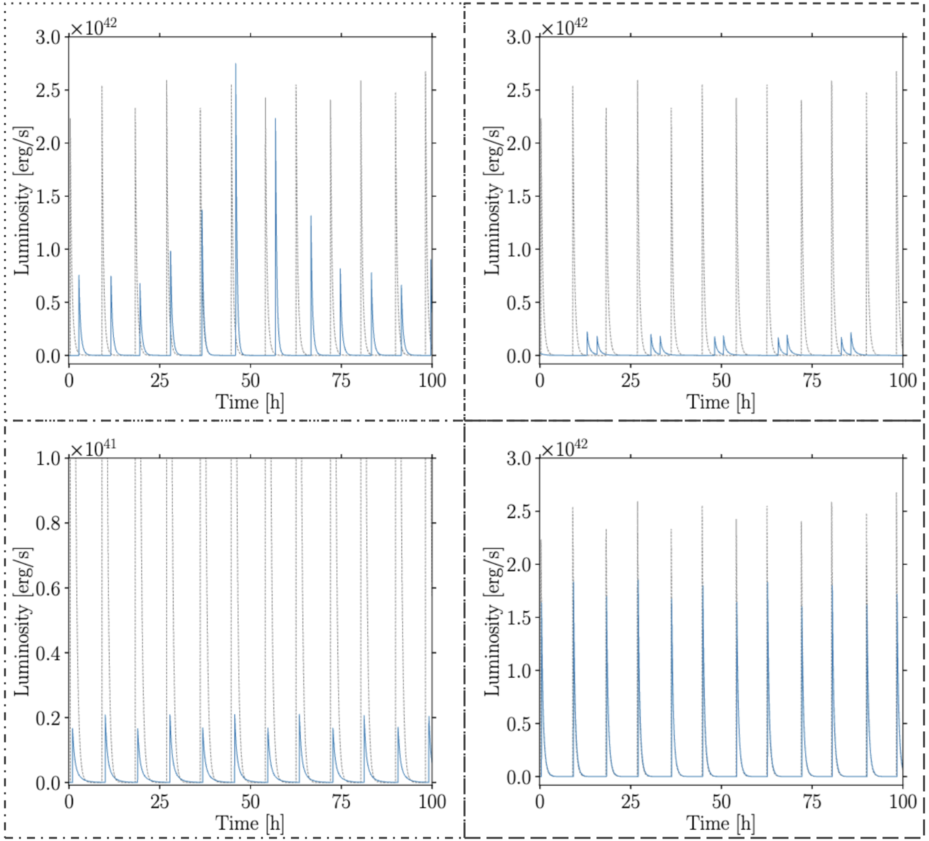
Varying model parameters in GSN

Higher MBH spin

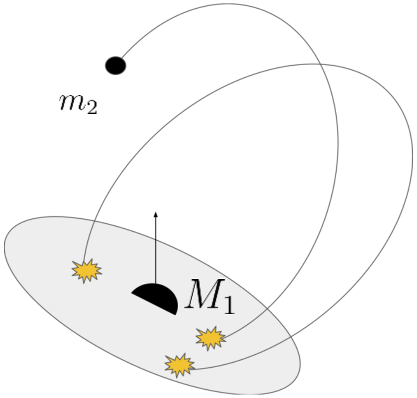
Higher EMRI eccentricity

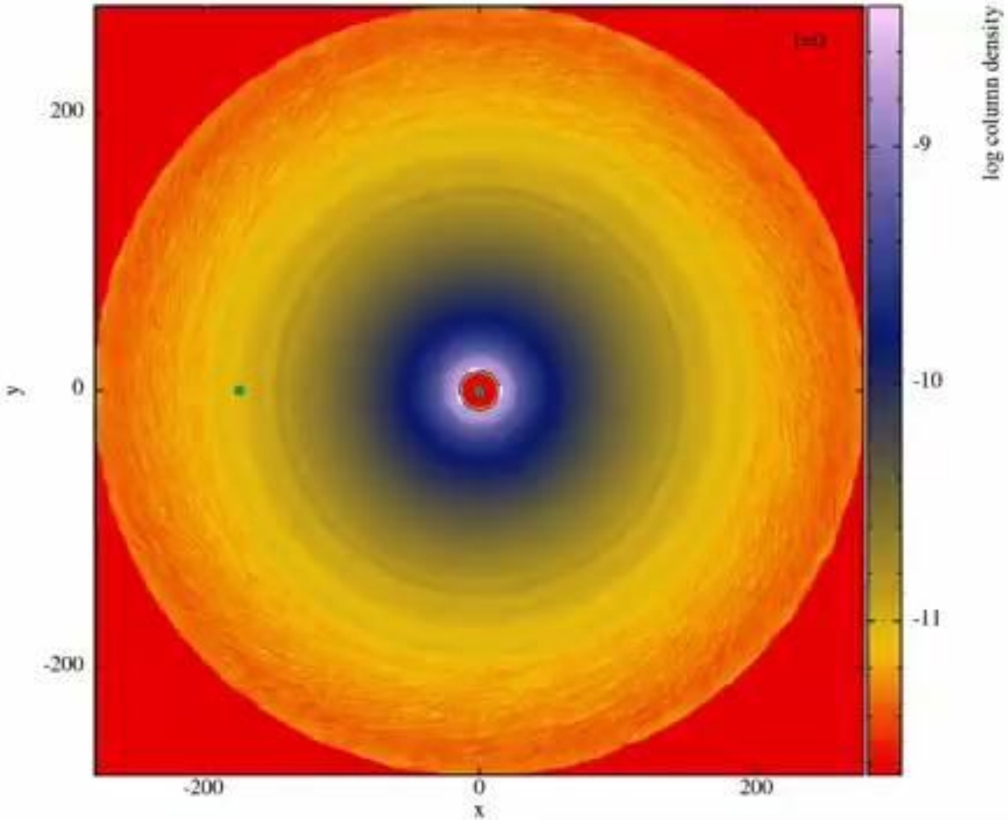
Retrograde EMRI

No disc precession



Impact simulations





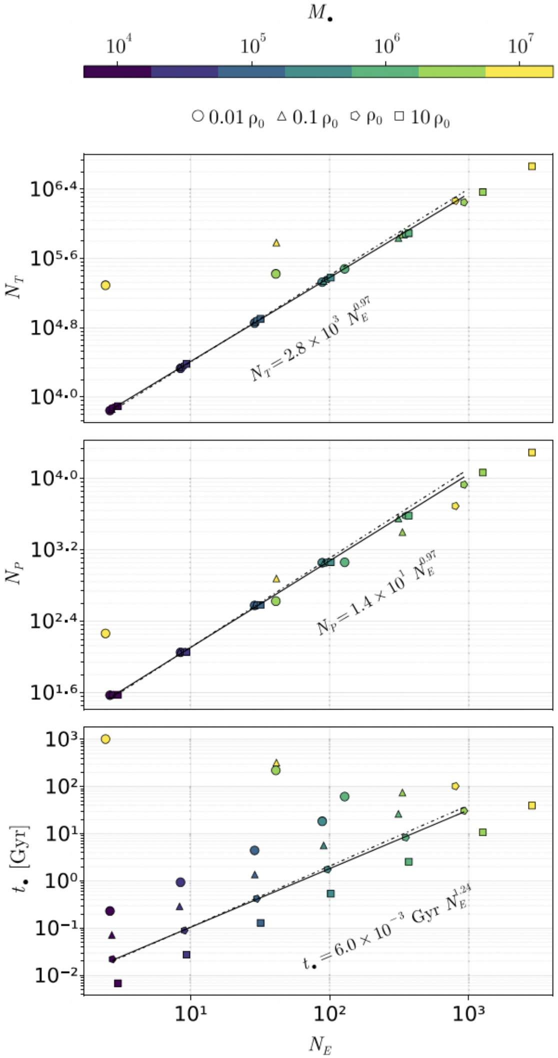
- PN terms
- radiation pressure
- black body cooling

Rates

Typical nuclear star clusters hosting the relatively low mass MBHs involved in QPEs feature short relaxation times (Broggi et al. 2022)

Assuming a typical evolved Kroupa stellar mass function, the number of stellar BHs is 10^{-3} that of normal stars at ~ 1pc

At ~ 100 R_g, the number density of stellar black holes is comparable to that of stars



Broggi et al. MNRAS 514 (2022)

Conclusions

- QPEs can be produced by an EMRI companion that crosses a rigidly precessing disc on a prograde orbit with low inclination with respect to the disc
- We assumed the disc to be formed by a TDE
- **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
- **Temperature ratio decreases with increasing quiescence rate**, consistent with observations (Miniutti et al. 2023)
- **QPEs can help in constraining the EMRI and TDEs populations**