Quasi Periodic Eruptions from EMRI-disc crossings

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

Quasi-Periodic Eruptions

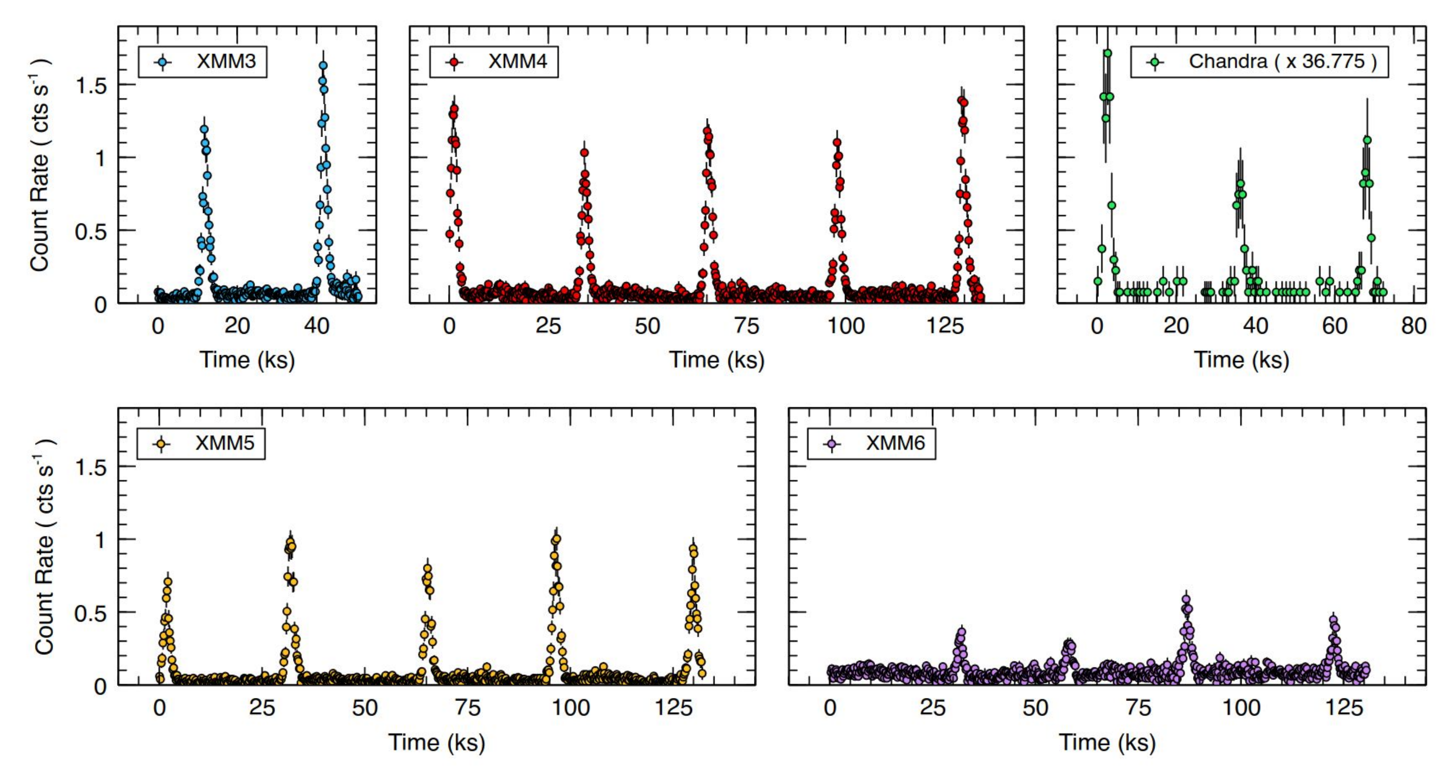
Quasi-Periodic Eruptions (**QPEs**, Miniutti+19, Giustini+20, Arcodia+21,22) are **electromagnetic extragalactic transient** phenomena associated with massive black holes (**MBHs**) hosted in galaxy centers.

They are **fast bursts in the soft X-ray band (0.2-2 keV)** superimposed to an otherwise stable quiescent X-ray level:

- thermal-like X-ray spectra with temperature running from $k_B T \sim 50$ eV to ~200 eV
- peak X-ray luminosity is $\sim 10^{42-43}$ erg/s, one order of magnitude above quiescence
- depending on the source, they last between $\lesssim 1$ hour and a few hours, and repeat every about 2.5 − 20 hours with a quasi-periodic pattern

Quasi-Periodic Eruptions

GSN 069 - Miniutti et al., Nature, 573, 7774 (2019), the first discovered QPE



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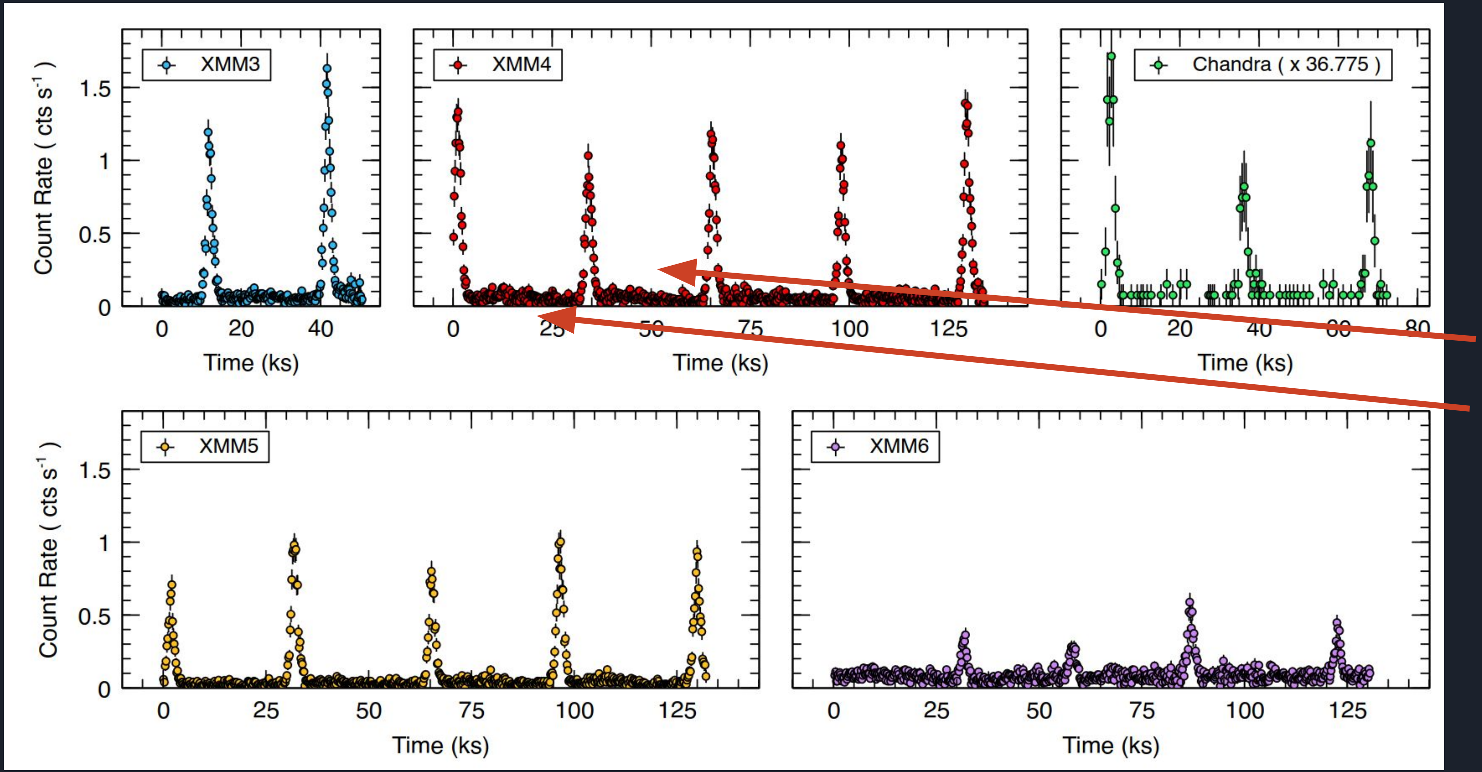
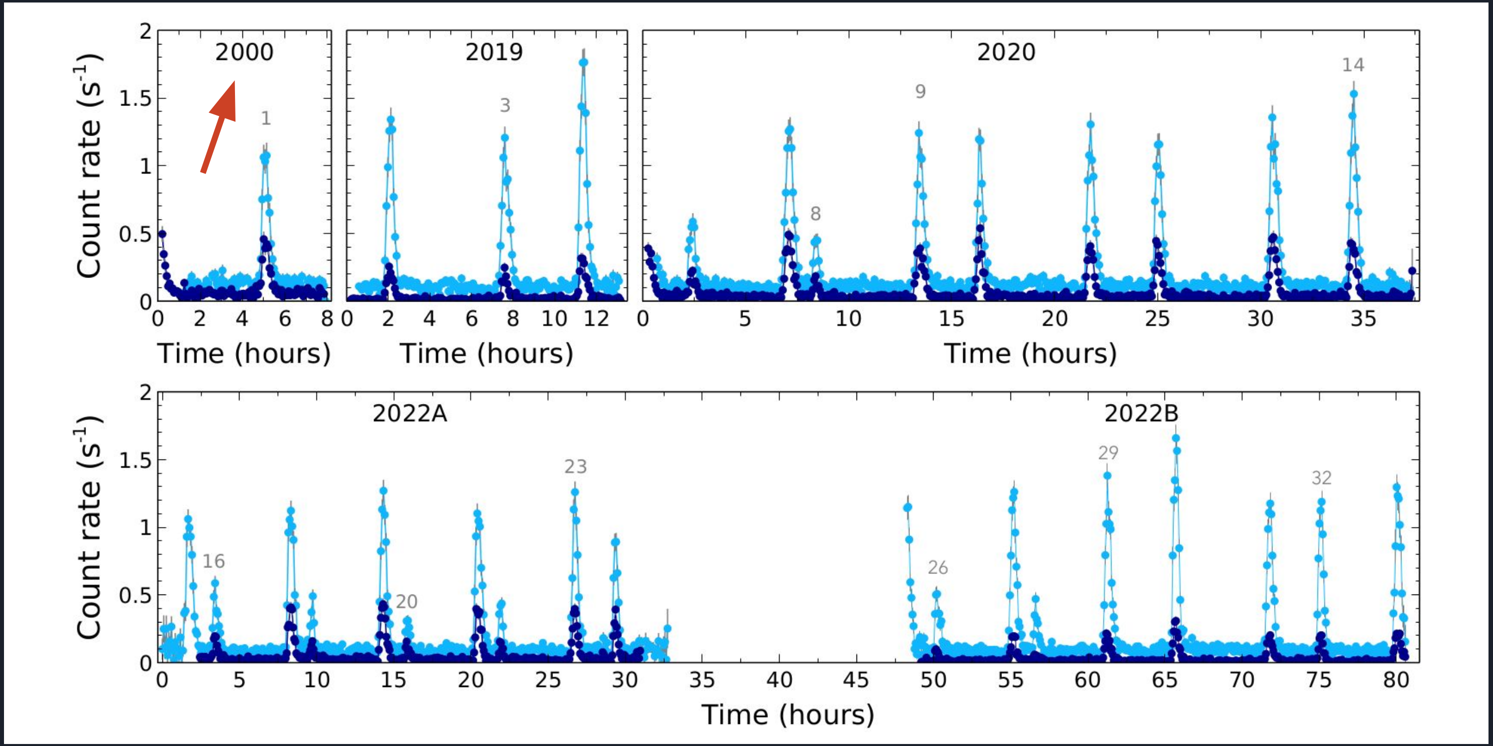


Recurrence time is quasi-periodic, a longer time interval is generally followed by a stronger QPE

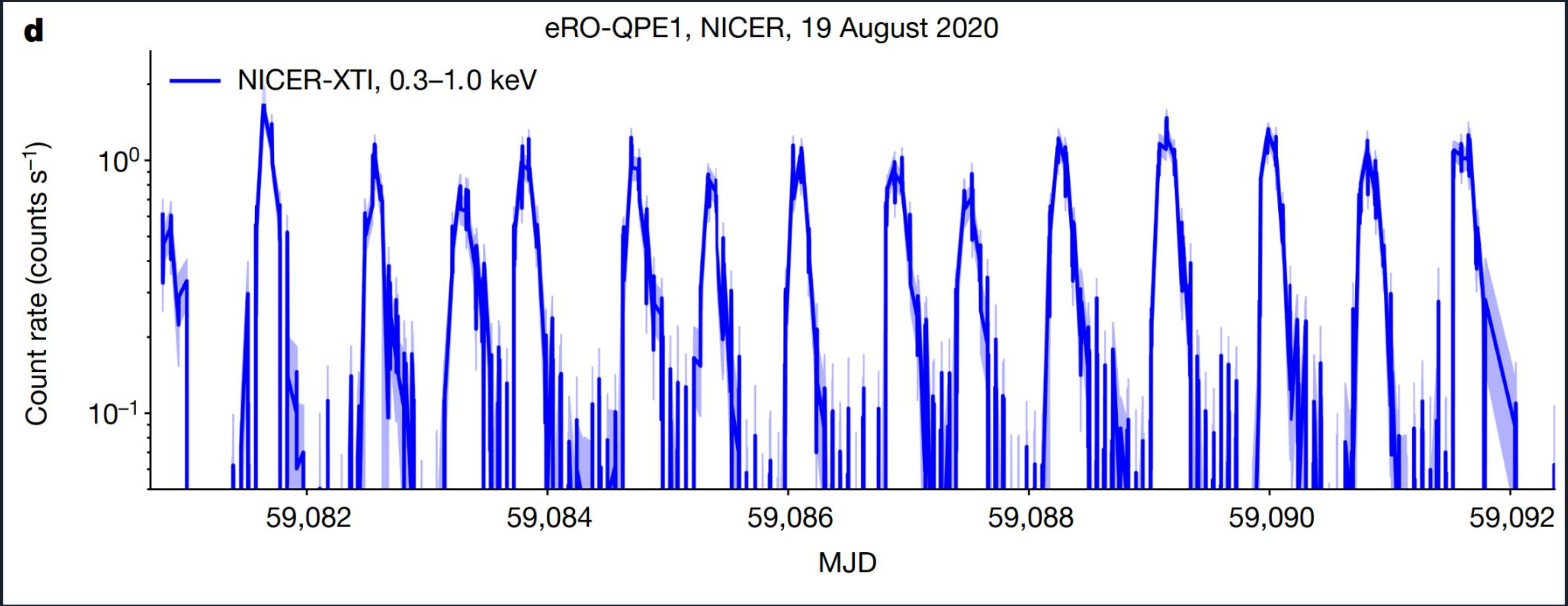
Quasi-Periodic Eruptions

RXJ - Giustini et al., A&A 636L 2 (2020), archival observations go back before 1990



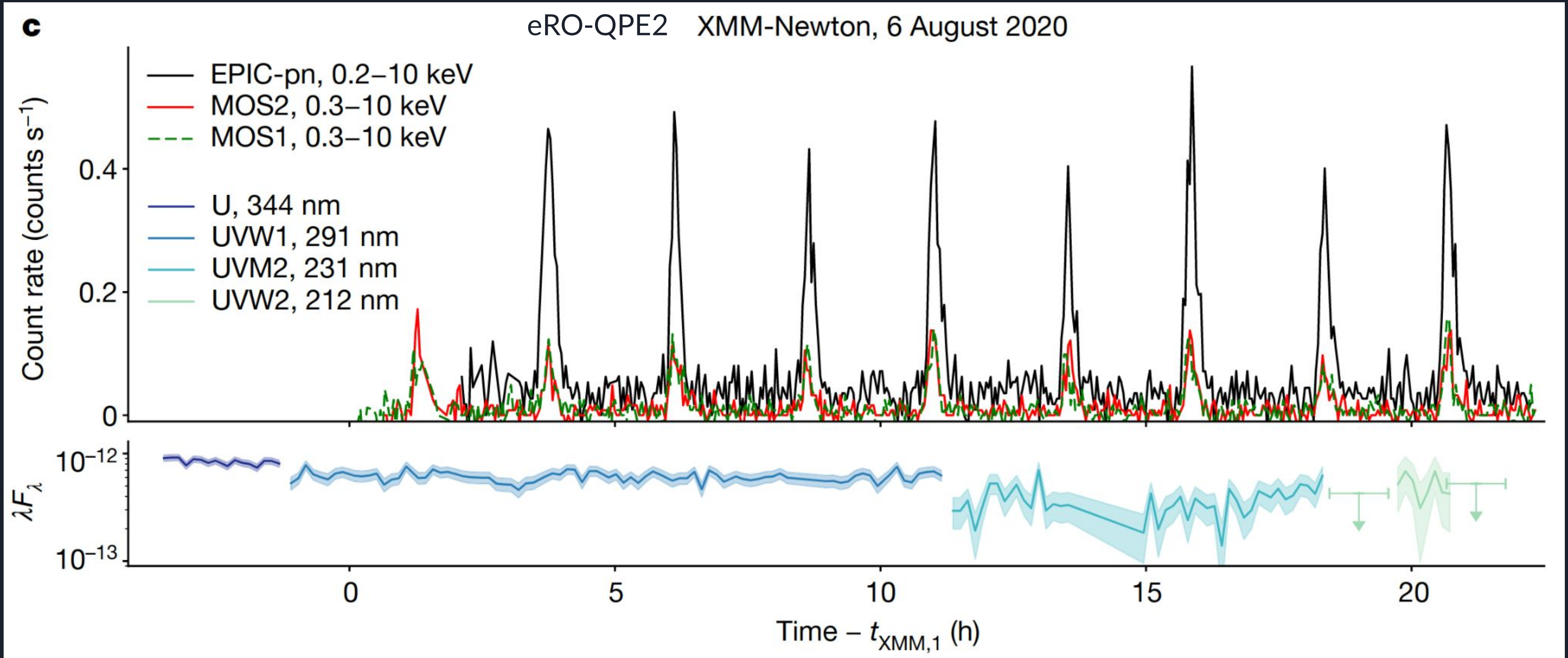
Quasi-Periodic Eruptions

eRO-QPE1 - Arcodia et al., Nature 592 704 (2020)



Quasi-Periodic Eruptions

eRO-QPE2 - Arcodia et al., Nature 592 704 (2020)



Quasi-Periodic Eruptions

We detected them, but what are QPE??

- Many telescopes detected them: XMM-Newton, Chandra, Swift, NICER, eROSITA!

Quasi-Periodic Eruptions

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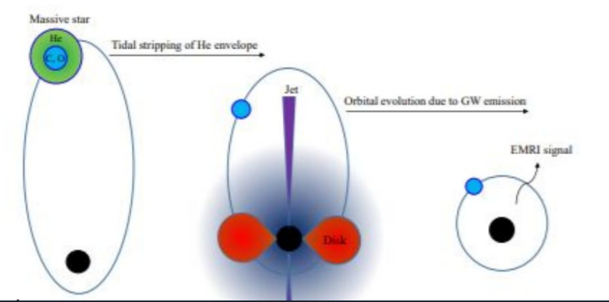
- Many telescopes detected them: XMM-Newton, Chandra, Swift, NICER, eROSITA

- Probably not aliens trying to contact us

Quasi-Periodic Eruptions

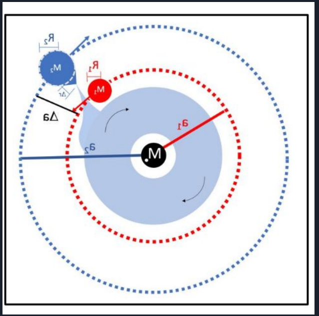


We detected them, but what are QPE??

The puzzling phenomenon has generated a quite large literature, we can divide the proposed models in two broad classes:

- **Accretion flow instabilities around the massive black hole** (Pan et al. 2022; Kaur et al. 2023; Pan et al. 2023; Śniegowska et al. 2023, Raj & Nixon 2021)

- **Orbital phenomena connected with other objects orbiting around the <u>active</u> massive black hole** (King 2020; Zhao et al. 2022; Metzger et al. 2022; Wang et al. 2022; King 2022; Krolik & Linial 2022; Lu & Quataert 2022; Linial & Sari 2023; King 2023; Suková et al. 2021; Xian et al. 2021; Linial & Metzger 2023; Franchini et al. 2023; Tagawa & Haiman 2023; Zhou et al. 2024)



Quasi-Periodic Eruptions

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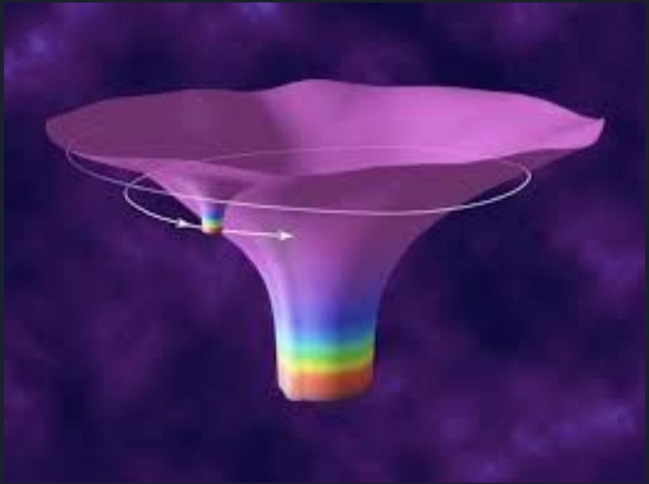
Quasi-Periodic Eruptions

Orbital phenomena connected with other objects orbiting around the <u>active</u> massive black hole

Here we have a so-called EMRI system - **Extreme mass-ratio inspiral -** a system characterised by a very unequal mass ratio, e.g. a MBH+stellar mass compact object



Those sources are very important sources for forthcoming LISA mission!

Small q -> quasi adiabatic inspiral -> huge number of orbital cycles

EMRI can precisely map the kerr-spacetime!

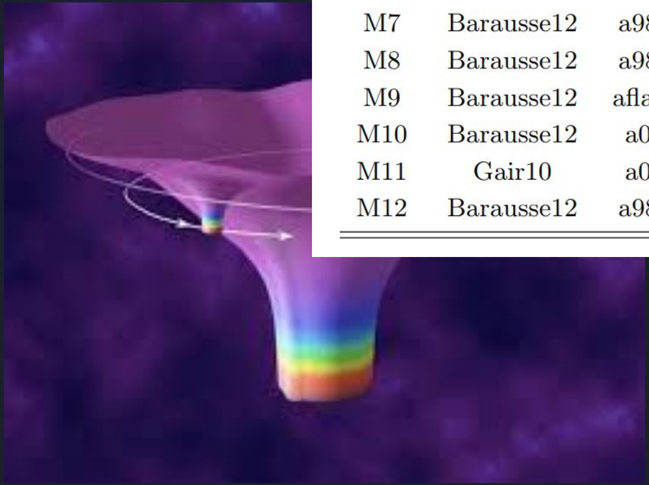
<u>Extremely poorly constrained formation rate!</u>

Quasi-Periodic Eruptions

Orb

Her
ver

Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass $[M_\odot]$	EMRI rate $[yr^{-1}]$ Total	Detected (AKK)	Detected (AKS)
M1	Barausse12	a98	yes	Gultekin09	10	10	1600	294	189
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400	220	146
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770	809	440
M4	Barausse12	a98	yes	Gultekin09	10	30	520 (620)	260	221
M5	Gair10	a98	no	Gultekin09	10	10	140	47	15
M6	Barausse12	a98	no	Gultekin09	10	10	2080	479	261
M7	Barausse12	a98	yes	Gultekin09	0	10	15800	2712	1765
M8	Barausse12	a98	yes	Gultekin09	100	10	180	35	24
M9	Barausse12	aflat	yes	Gultekin09	10	10	1530	217	177
M10	Barausse12	a0	yes	Gultekin09	10	10	1520	188	188
M11	Gair10	a0	no	Gultekin09	100	10	13	1	1
M12	Barausse12	a98	no	Gultekin09	0	10	20000	4219	2279



Extremely poorly constrained formation rate!

An EM-informed insight on the EMRI population will be highly desirable!!

Quasi-Periodic Eruptions - mass transfer

Orbital phenomena connected with other objects orbiting around the active massive black hole

- eccentric and circular orbits of single or multiple stars or stellar remnants, experiencing **Roche Lobe overflow** or **tidal stripping** at each pericenter passage.

X-ray here are generated by the bursty accretion on the MBH, the timing is regulated by the orbital period of the star

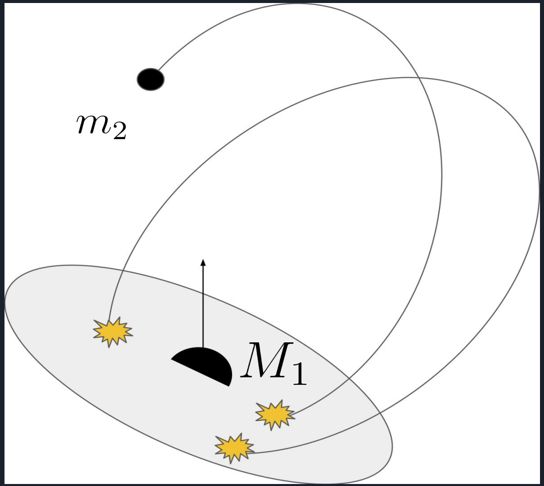
↓

One QPE per orbit

Quasi-Periodic Eruptions - impacts

Orbital phenomena connected with other objects orbiting around the active massive black hole

- **impacts of an EMRI on the accretion flow** around the MBH. The time separation between impacts depend on the EMRI orbital semi-major axis and eccentricity



X-ray here are generated by the shocked gas that is pulled out from the accretion disk

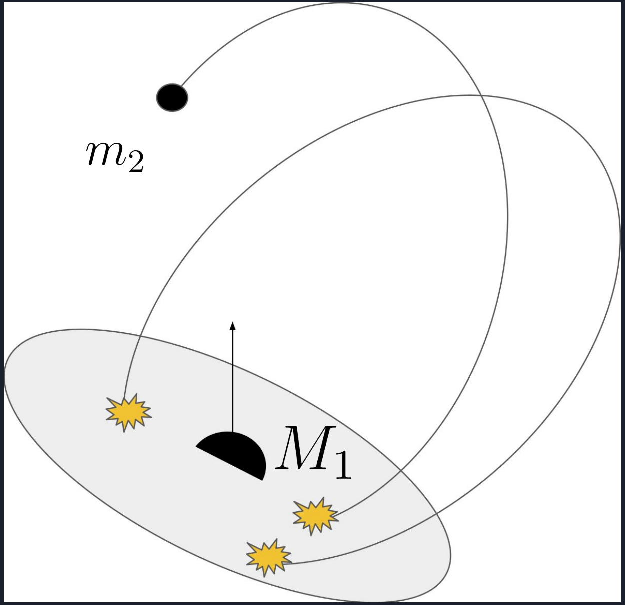
↓

QPEs happen (at least) twice per orbit

Metzger et al. 2022; Wang et al. 2022; Lu & Quataert 2022; Linial & Sari 2023; King 2023; Suková et al. 2021; Xian et al. 2021; Linial & Metzger 2023; Franchini et al. 2023; Tagawa & Haiman 2023; Zhou et al. 2024

Quasi-Periodic Eruptions - Dynamical model

We model the QPE emission considering an EMRI system crossing a misaligned accretion disk



- Post-Newtonian evolution of the EMRI (3.5PN + 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)

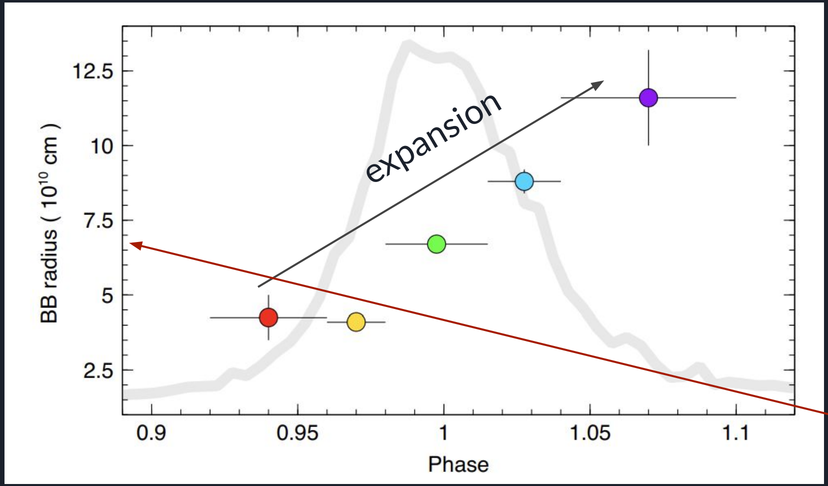
$$\Omega_p = \frac{\int_{R_{\rm ISCO}}^{R_{\rm out}} \Omega_{\rm LT}(R)L(R)2\pi R dR}{\int_{R_{\rm ISCO}}^{R_{\rm out}} L(R)2\pi R dR}$$

Combining 3 different precession frequencies we can produce quasi periodicities!

Quasi-Periodic Eruptions - Emission model

We model the QPE emission considering an EMRI system crossing a misaligned accretion disk

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



$$R_{\mathrm{in}} \sim R_{\mathrm{inf}} = \frac{GM_2}{c_s^2 + v_{\mathrm{rel}}^2}$$

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

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

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

Inclination has to be small to make R_{in} ~ 10^{11} cm

Quasi-Periodic Eruptions - Comparison

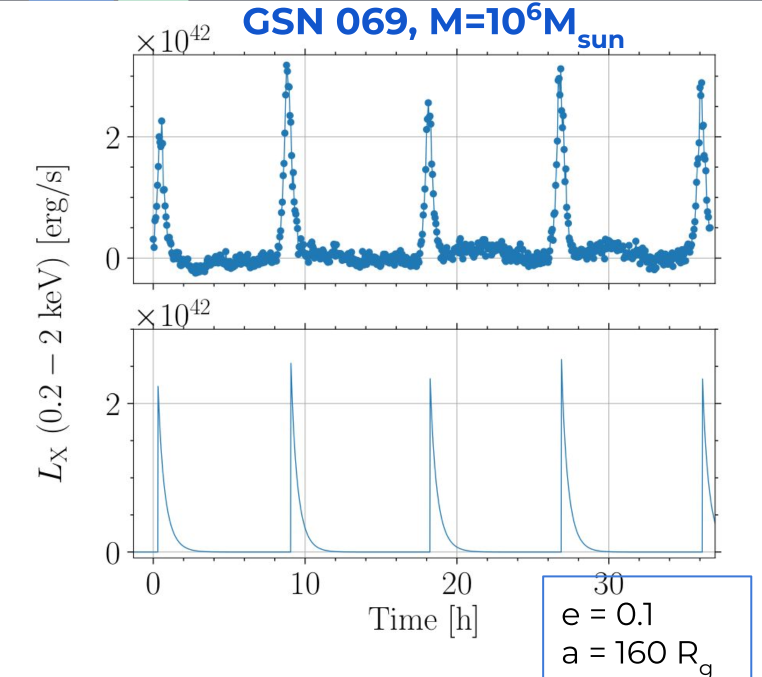


Fig. 3. Upper panel: 0.2-2 keV quiescence-subtracted X-ray luminosity light curve from the *XMM-Newton* observation XMM5 of GSN 069 (Miniutti et al. 2023). Lower panel: synthetic light curve obtained with the parameters listed in Sect. 3.1.1.

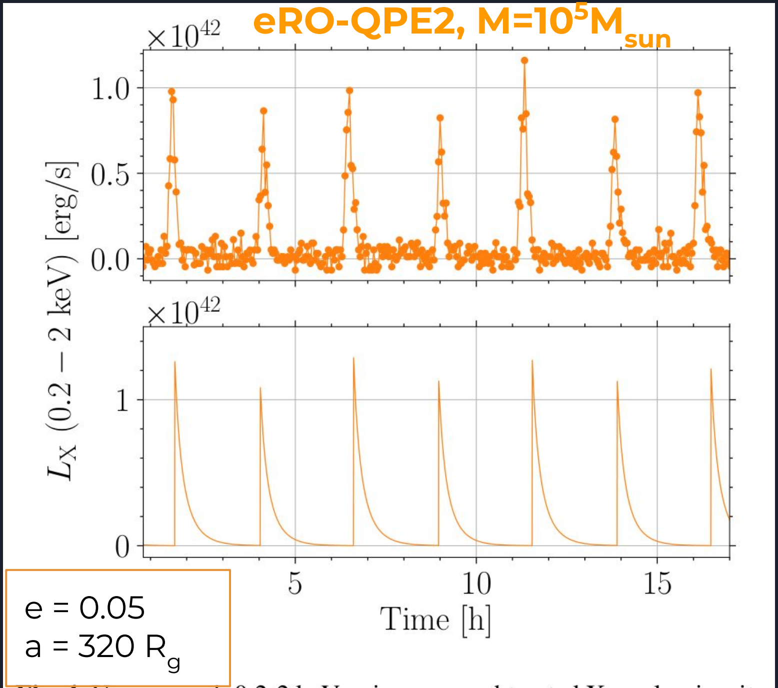


Fig. 4. Upper panel: 0.2-2 keV quiescence-subtracted X-ray luminosity light curve from one of the *XMM-Newton* observations of eRO-QPE2. Lower panel: synthetic light curve obtained with the parameters listed in Sect. 3.1.2.

Quasi-Periodic Eruptions - Comparison

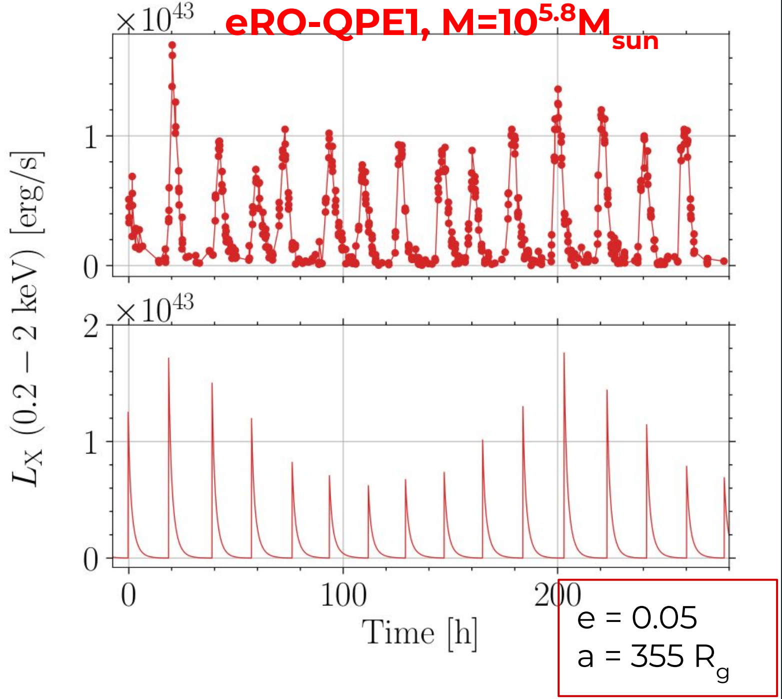


Fig. 5. Upper panel: 0.2-2 keV X-ray luminosity light curve from a *NICER* ~ 250 hr-long monitoring of eRO-QPE1. The quiescent level is undetected by *NICER*. Lower panel: synthetic light curve obtained with the parameters listed in Sect. 3.1.3.

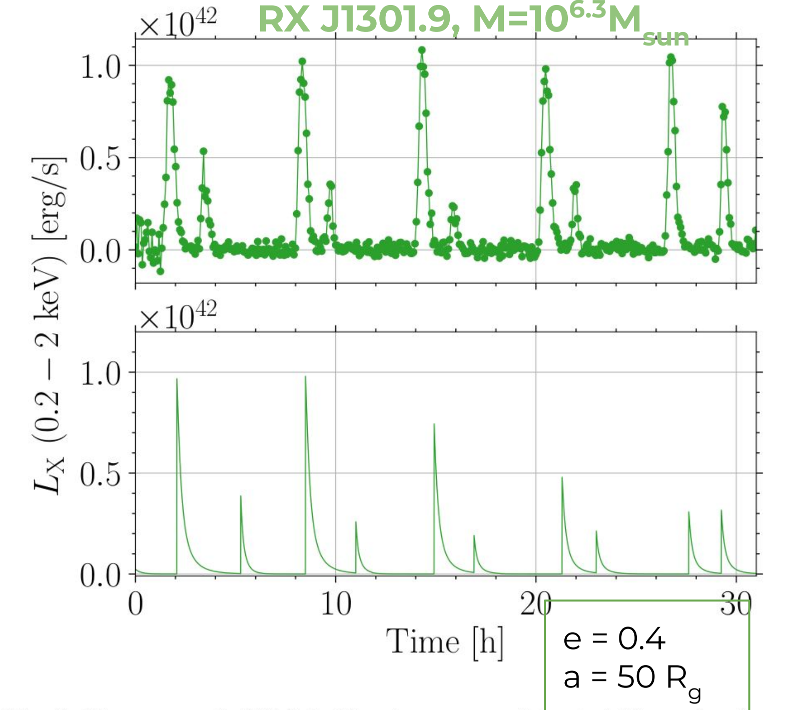


Fig. 6. Upper panel: 0.2-2 keV quiescence-subtracted X-ray luminosity from one of the *XMM-Newton* observations of RX J1301.9+2747. Lower panel: synthetic light curve obtained with the parameters listed in Sect. 3.1.4.

Quasi-Periodic Eruptions - Complications

Ticking away: the long-term X-ray timing and spectral evolution of eRO-QPE2

R. Arcodia*[1], I. Linial[2,3], G. Miniutti[4], A. Franchini[5,6], M. Giustini[4], M. Bonetti[6,7], A. Sesana[6,7,11], R. Soria[8,9], J. Chakraborty[1], M. Dotti[6,7], E. Kara[1], A. Merloni[10], G. Ponti[11,10] F. Vincentelli[12]

Observations seems to hint an evolution of the recurrence time over 3 years

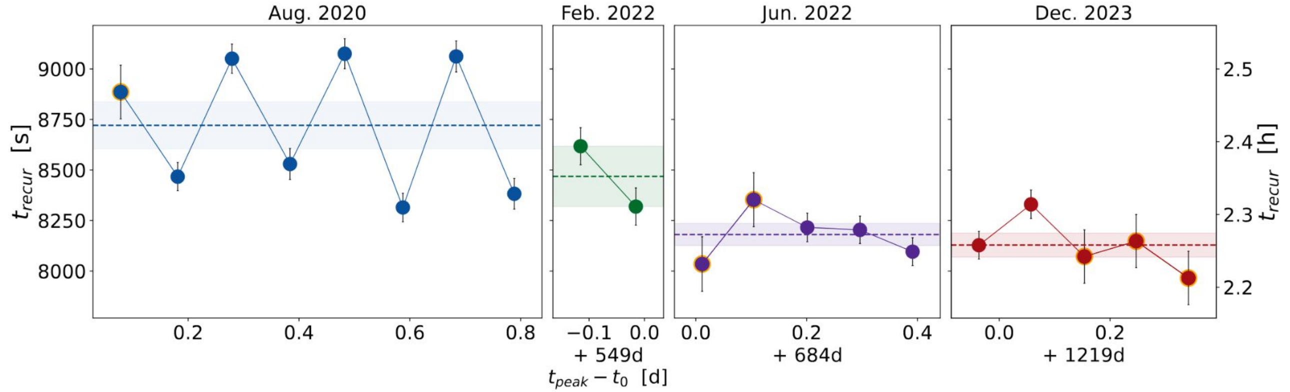


Fig. 2. Evolution of the recurrence time between eruptions over the ~ 3.3 yr baseline. The start time t_0 represents the start of the Aug. 2020 observation. Data points with an orange contour contain an additional systematic uncertainty, as described in the text. The mean value in each epoch, with associated standard error of the mean, is shown with a dashed line and shaded contours.

GSN069

Quasi-Periodic Eruptions - Complications

Alive and kicking: A new QPE phase in GSN 069 revealing a quiescent luminosity threshold for QPEs

G. Miniutti[1,⋆], M. Giustini[1], R. Arcodia[2,⋆⋆], R. D. Saxton[3], J. Chakraborty[2], A. M. Read[4], and E. Kara[2]

QPE properties changed after re-brightening

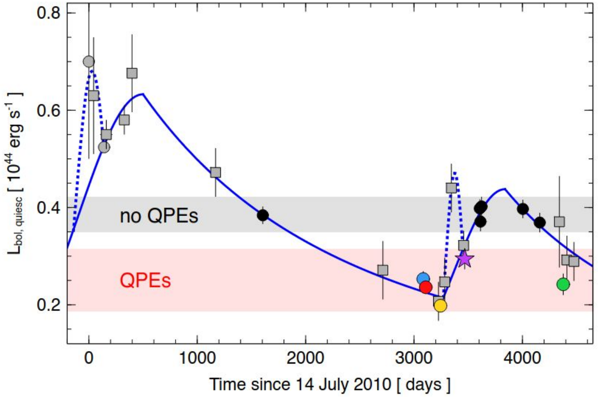


Fig. 4. Quiescent luminosity long-term evolution. Shown is the L_{bol} evolution of the quiescent emission over the past ~ 12 yr. The dotted-solid line is a possible model discussed in Miniutti et al. (2023). The grey data points refer to observations that are too short to ensure the detection of QPEs (squares for *Swift* and circles for *XMM-Newton* data). Coloured and black data points represent instead long enough observations respectively with and without QPEs. The purple star denotes the XMM6 observation with irregular QPEs. A *Chandra* observation (exhibiting three QPEs) performed between the XMM4 and XMM5 observations was omitted as the corresponding quiescent luminosity is highly uncertain (see Table D.1).

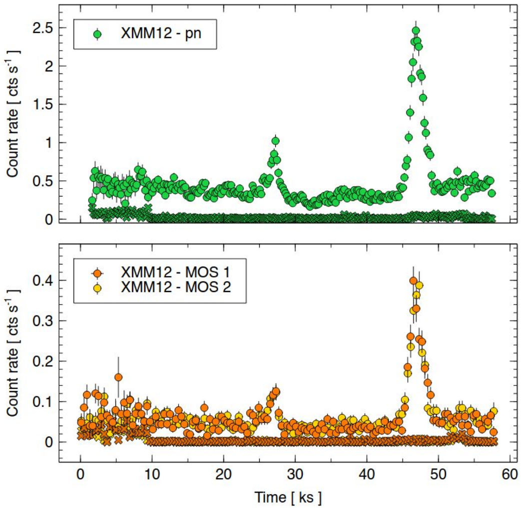


Fig. 1. EPIC light curves from the XMM12 observation. Light curves in the 0.2-1 keV with time bins of 200 s (pn) and 400 s (MOS) are shown. Background light curves, rescaled to the same extraction area, are also shown to highlight the slightly higher background during the initial ~ 10 ks of the EPIC exposures. The start of the MOS 1 exposure is taken as origin for the time-axis in all cases.

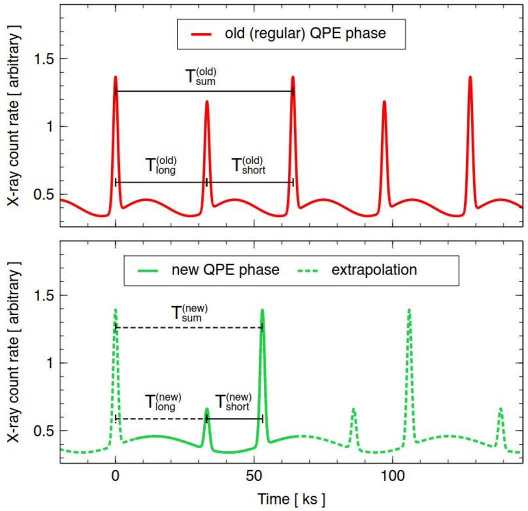
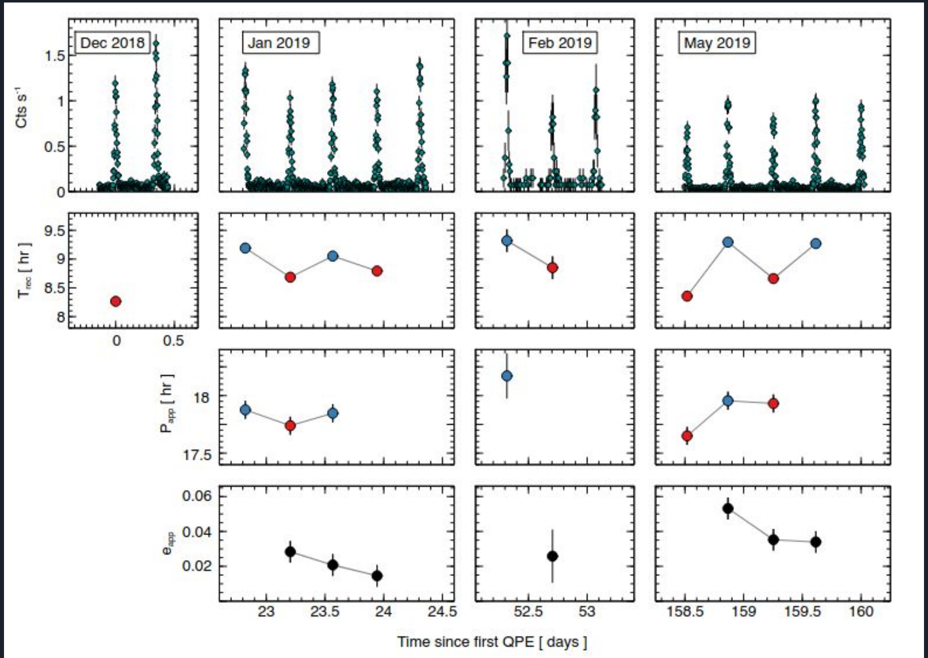


Fig. 3. Comparison between old and new QPE phases. Upper panel: Typical model light curve for observations during the old regular QPE phase. Lower panel: Qualitative representation of the light curve from the XMM12 observation (new QPE phase; solid line) and one possible extrapolation of longer-term behaviour based on the arguments discussed in Sect. 3 and Appendix A (dashed line). The light curves were normalised so that the intensity of the strong QPEs is the same in both panels. The same quiescent level is assumed for visual clarity.

Quasi-Periodic Eruptions - Complications

***Eppur si muove*: Evidence for disc precession or a sub-milliparsec SMBH binary in the QPE-emitting galaxy GSN 069**

G. Miniutti*[1], A. Franchini[2,3], M. Bonetti[3,4], M. Giustini[1], J. Chakraborty[5], R. Arcodia**[5], R. Saxton[6], E. Quintin[7], P. Kosec[8], I. Linial[9,10], and A. Sesana[3,4]



O-C analysis of QPE recurrence revealed a sinusoidal modulation

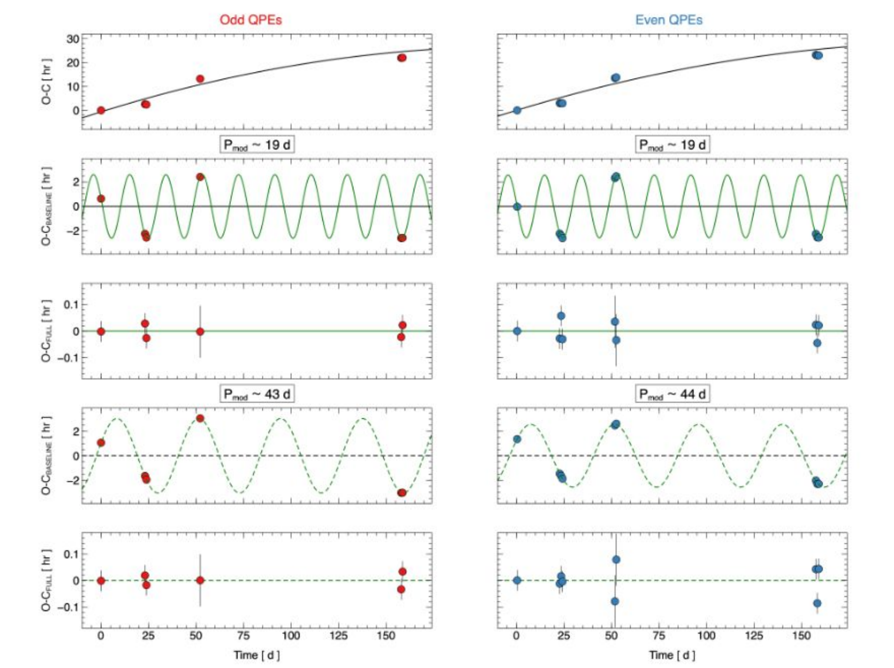


Fig. 4. O-C diagrams for GSN 069. We show the O-C diagrams for odd (left) and even (right) QPEs for GSN 069 resulting from identifying the first QPE of the May 2019 observation with the 211th even QPE. The upper panels show the O-C data together with the linear plus parabolic baseline model for $P_{mod} \simeq 19$ d. The lower panels show the corresponding residuals (O-$C_{BASELINE}$) as well as the ones corresponding to the full best-fitting model including a sinusoidal modulation (O-C_{FULL}) for the two possible P_{mod}. The sinusoidal modulation is also shown in the O-$C_{BASELINE}$ to guide the eye.

Quasi-Periodic Eruptions - Complications

Fragments of harmony amid apparent chaos: a closer look at the X-ray quasi-periodic eruptions of the galaxy RX J1301.9+2747

Margherita Giustini[1], Giovanni Miniutti[1], Riccardo Arcodia[2], Adelle Goodwin[3], Kate D. Alexander[4], Joheen Chakraborty[2], Johannes Buchner[5], Peter Kosec[6], Richard Saxton[7], Matteo Bonetti[8, 9, 10], Alessia Franchini[11, 9, 12], Taeho Ryu[13], Xinwen Shu[14], Erin Kara[2], Gabriele Ponti[15, 5], Erwan Quintin[16], Federico Vincentelli[17, 18], Natalie Webb[16], Jari Kajava[19], and Sebastiano D. von Fellenberg[20]

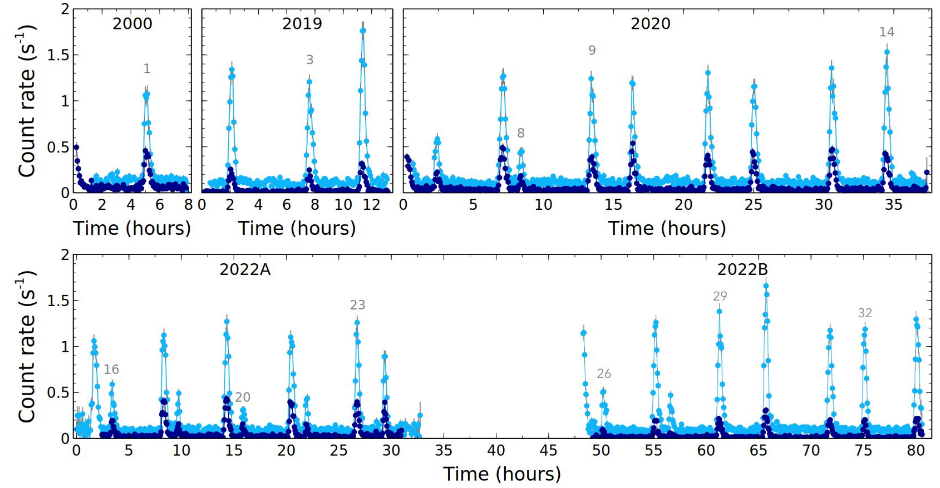


Fig. 1: Background-corrected *XMM-Newton* light curves of RX J1301.9+2747, extracted with time bins of 250 s in the 0.2 – 2 keV
n light blue, by the MOS in dark blue. The epoch of observation name used in the text as explained in
panel. We number QPEs from number 0 (half-detected by the MOS in 2000) to number 33 (the last
k few of them with grey numbers.

The complicated pattern of RXJ is still puzzling!!

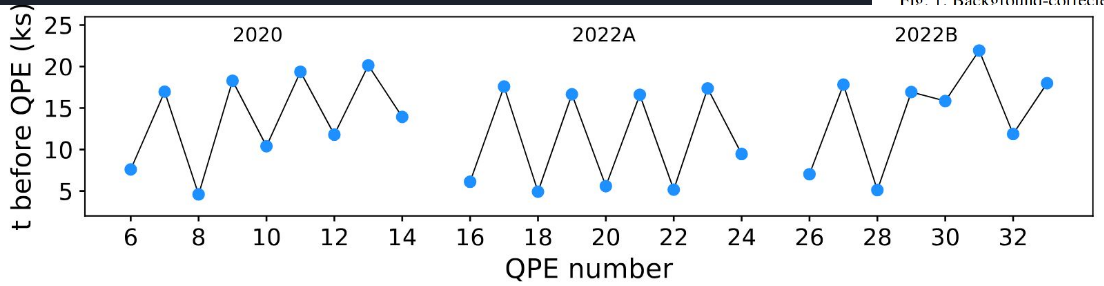


Fig. 3: Time (in ks) preceding each QPE of the 2020, 2022A, and 2022B *XMM-Newton* observations of RX J1301.9+2747.

Quasi-Periodic Eruptions - Complications

The long term variability/modulation of the QPE pattern might be ascribed to different reasons

- Different nature of the secondary object: main sequence stars can experience mass ablation, this can give insight into the viscous drag in an accretion disc. Still stars can get tidally destroyed, in most of QPE objects stars are within the tidal radius

- Modulation of QPE pattern: The disc precession can impact the QPE timing and can be responsible for the modulation highlighted by the O-C analysis. The presence of a third object might also modulate the pattern. Disc precession is however expected to damp as the disc evolve over time. Longer observations might distinguish between different scenarios!

Quasi-Periodic Eruptions - Light curve

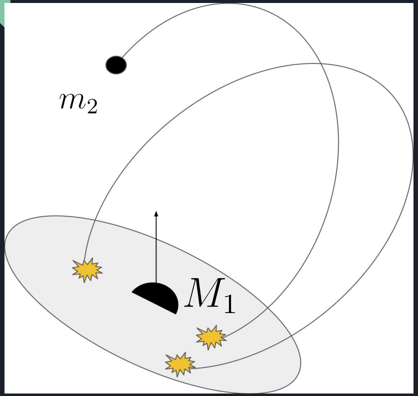
Much effort has been directed into the characterisation of the QPE timing, but much less into the light curve modelisation

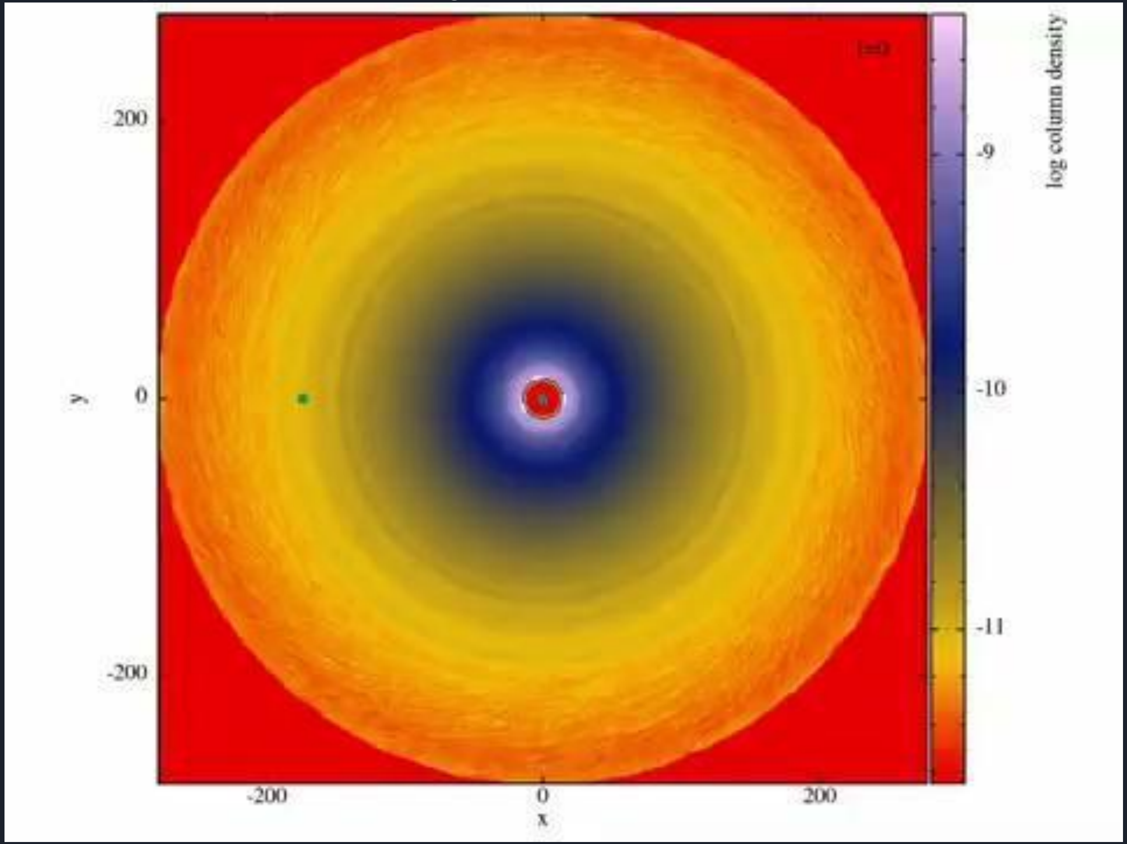
Existing estimated are based on analytical prescription or derived from semi-analytical calculations. Those unfortunately cannot capture the full story!

Full hydrodynamical simulations could shed light onto the specific process causing the QPE

Preliminary

Quasi-Periodic Eruptions - Hydro simulation



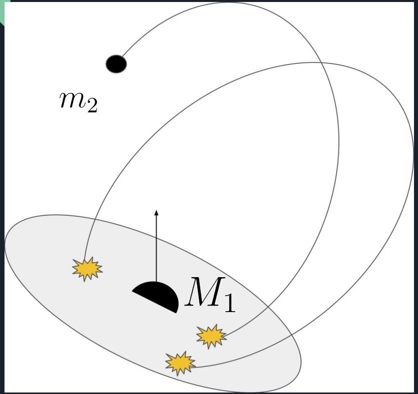


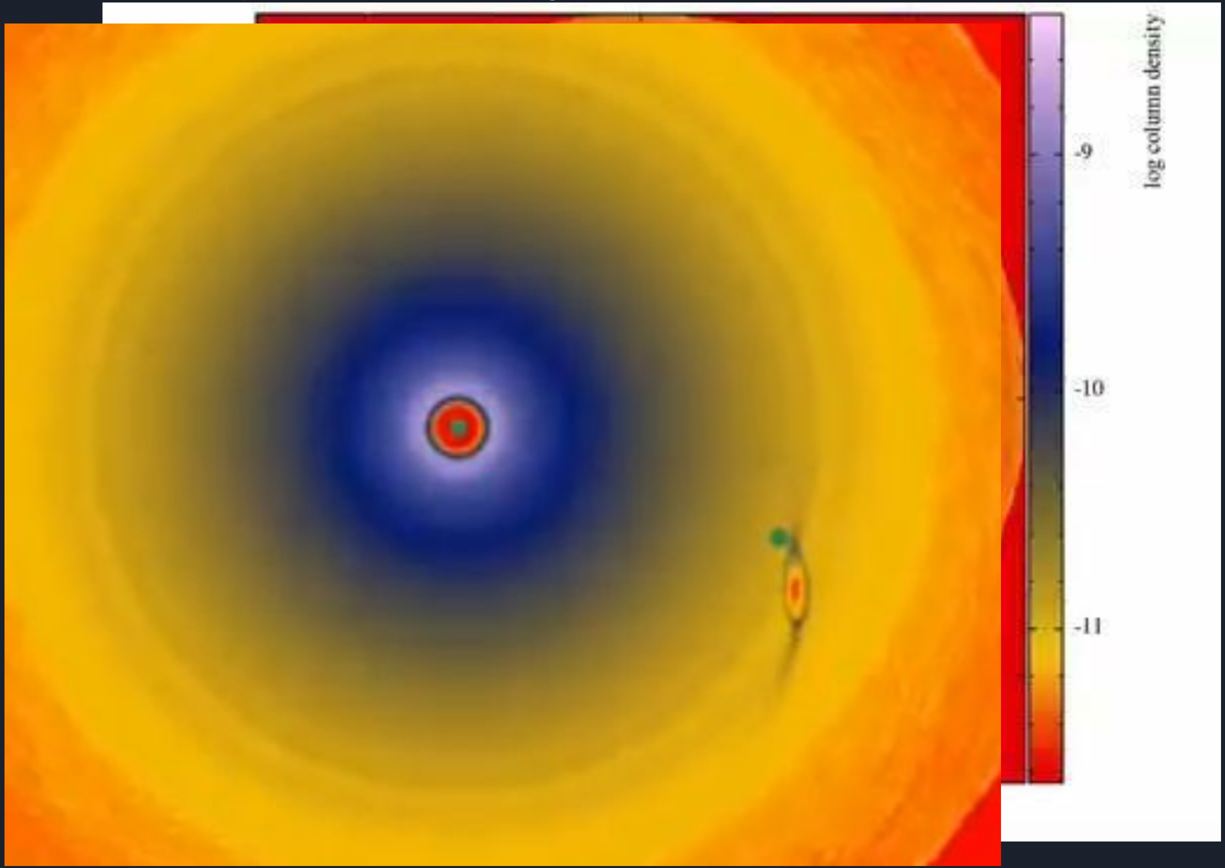
- PN terms
- radiation pressure
- black body cooling

Franchini, Lupi, Bonetti in prep.

Preliminary

Quasi-Periodic Eruptions - Hydro simulation





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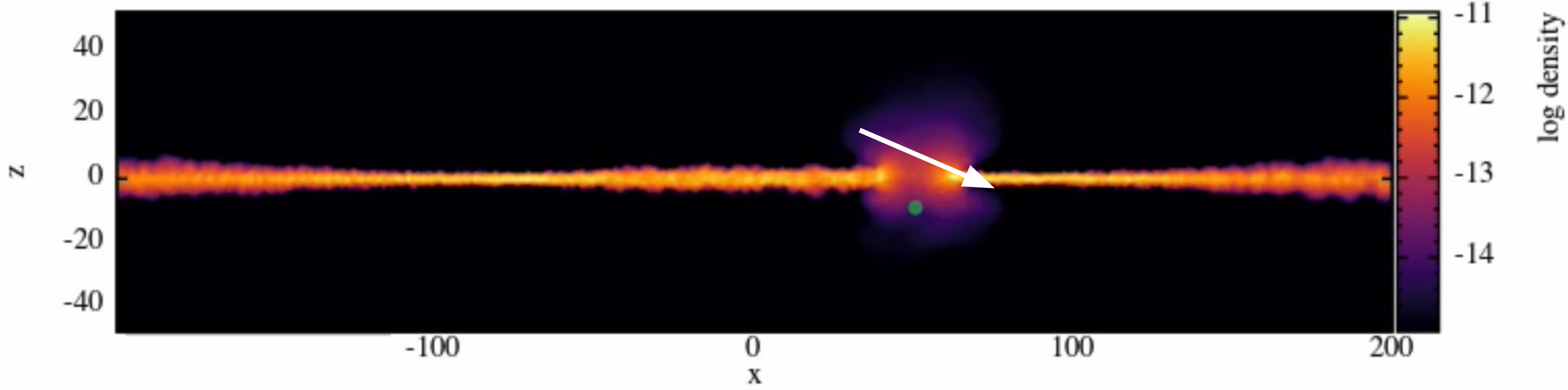
Preliminary

Quasi-Periodic Eruptions - Hydro simulation



Franchini, Lupi, Bonetti in prep.

Conclusions

- In our model, 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, 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

- The combination of the apsidal and nodal precession frequency of the EMRI and the nodal precession frequency of the disc can reproduce the observed variety of QPE periodicities

- The observed systems however show a quite large of complexities that call for different explanations and modelisations might be increased to capture the underlying physics (external perturbations, hydro sims …)

- **QPEs can help in constraining the EMRI populations, possibly giving estimates for rates of LISA detection**