

# X-ray Quasi-Periodic Eruptions from two previously quiescent galaxies

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**Quasi-Periodic Eruptions (QPEs) are extreme high-amplitude bursts of X-ray radiation recurring every few hours and originating near the central supermassive black holes in galactic nuclei<sup>1,2</sup>. It is currently unknown what triggers these events, how long they last and how they are connected to the physical properties of the inner accretion flows. Previously, only two such sources were known, found either serendipitously or in archival data<sup>1,2</sup>, with emission lines in their optical spectra classifying their nuclei as hosting an actively accreting supermassive black hole<sup>3,4</sup>. Here we present the detection of QPEs in two further galaxies, obtained with a blind and systematic search over half of the X-ray sky. The optical spectra of these galaxies show no signature of black hole activity, indicating that a pre-existing accretion flow typical of active nuclei is not required to trigger these events. Indeed, the periods, amplitudes and profiles of the newly discovered QPEs are inconsistent with current models that invoke radiation-pressure driven accretion disk instabilities<sup>5-9</sup>. Instead, QPEs might be driven by an orbiting compact object. Furthermore, their observed properties require the mass of the secondary object to be much smaller than the main body<sup>10</sup> and future X-ray observations may constrain possible changes in the period due to orbital evolution. This scenario could make QPEs a viable candidate for the electromagnetic counterparts of the so-called extreme mass ratio inspirals<sup>11-13</sup>, with considerable implications for multi-messenger astrophysics and cosmology<sup>14,15</sup>.**

Given its large collecting area and blind survey strategy, SRG/eROSITA<sup>16</sup> is capable of systematic searches for X-ray sources which are variable on timescales of hours to months (see Methods for more details). This applies to QPEs, which thus far have only been detected in X-rays<sup>1,2</sup>. The first QPE discovered by eROSITA, hereafter eRO-QPE1, showed high-amplitude X-ray variability within just a few hours. It showed a strong X-ray signal in two eROSITA survey scans which were preceded, separated and followed by scans showing it to be much fainter (Fig. 1a). Like the two previously known QPE sources, GSN 069<sup>1</sup> and RX J1301.9+2747<sup>2</sup>, the X-ray spectrum is very soft with most of the counts originating from below  $\sim 1.5$ -2 keV and consistent with a thermal black-body emission. As with the light curve, the spectrum shows oscillations from a faint to a bright

phase (Fig. 1b). We identify eRO-QPE1 as originating within the nucleus of the galaxy 2MASS 02314715-1020112, for which we measured a spectroscopic redshift of  $z=0.0505$  (see Methods, ‘The host galaxies of QPEs’). The related eROSITA quiescence ( $1\sigma$  upper limit) and peak intrinsic 0.5-2 keV luminosities are  $<2.1 \times 10^{41}$  and  $\sim 9.4 \times 10^{42}$  erg  $s^{-1}$ , respectively, if the X-ray spectra are modeled with a standard accretion disk model (see Methods, ‘X-ray spectral analysis’).

Two follow-up observations triggered with the XMM-Newton X-ray telescope confirmed the remarkable bursting nature of the source (Fig. 1c and 1d). The first observation (hereafter eRO-QPE1-XMM1) found the source in a faint state for  $\sim 30$  ks, followed by a sequence of three consecutive asymmetric bursts, possibly partially overlapping (Fig. 1c), behaviour which has not been observed before in QPEs<sup>1,2</sup>. In terms of intrinsic 0.5-2 keV luminosity, after an initial quiescent phase at  $\sim 2.3 \times 10^{40}$  erg  $s^{-1}$  the first burst was characterised by a fast rise and slower decay lasting  $\sim 30$  ks and peaking at  $\sim 3.3 \times 10^{42}$  erg  $s^{-1}$ ; it was then followed by a second fainter burst (peak at  $\sim 7.9 \times 10^{41}$  erg  $s^{-1}$ ) and by a third, which was the brightest (peak at  $\sim 2.0 \times 10^{43}$  erg  $s^{-1}$ ) but was only caught during its rise. The second XMM-Newton observation (hereafter eRO-QPE1-XMM2) showed an eruption very similar to the first seen in eRO-QPE1-XMM1 in terms of amplitude and luminosity, although lasting for  $>40$  ks, namely for almost as much as the three in eRO-QPE1-XMM1 combined (Fig. 1c). To better characterise the physics and to determine the duty cycle of these eruptions, we started an intense monitoring campaign with the NICER X-ray instrument aboard the International Space Station (ISS), which revealed 15 eruptions in about 11 days (Fig. 1d).

The second new eROSITA QPE, hereafter eRO-QPE2, showed similar variability patterns and X-ray spectra as eRO-QPE1 during the X-ray sky survey (Fig. 2a and 2b). We associated it with the galaxy 2MASX J02344872-4419325 and determined a spectroscopic redshift of  $z=0.0175$  (see Methods, ‘The host galaxies of QPEs’). The related intrinsic 0.5-2 keV luminosity of the quiescent ( $1\sigma$  upper limit) and peak phase is  $<4.0 \times 10^{40}$  erg  $s^{-1}$  and  $\sim 1.0 \times 10^{42}$  erg  $s^{-1}$ , respectively. A follow-up observation with XMM-Newton revealed 9 eruptions in a single day, oscillating between  $\sim 1.2 \times 10^{41}$  erg  $s^{-1}$  and  $\sim 1.2 \times 10^{42}$  erg  $s^{-1}$  in the 0.5-2 keV band (Fig. 2c). In neither eRO-QPE1 nor eRO-QPE2 is there evidence of simultaneous optical/UV variability (see Fig. 1c and 2c), in agreement with the behaviour of GSN 069<sup>1</sup>.

eRO-QPE1 shows a range of QPE rise-to-decay duration with a mean (dispersion) of  $\sim 7.6$  hours ( $\sim 1.0$  hours) and peak-to-peak separations of  $\sim 18.5$  hours ( $\sim 2.7$  hours), as derived from the NICER light curve (Fig. 1d). The duty-cycle (mean duration over mean separation) is  $\sim 41\%$ . Conversely, eRO-QPE2 shows much narrower and more frequent eruptions (see Fig. 2c): the mean (dispersion) of the rise-to-decay duration is  $\sim 27$  minutes ( $\sim 3$  minutes), with a peak-to-peak separation of  $\sim 2.4$  hours ( $\sim 5$  minutes) and a duty-cycle of  $\sim 19\%$ . Interestingly, compared to the two previously known QPEs<sup>1,2</sup>, eRO-QPE1 and eRO-QPE2 extend the parameter space of QPE widths and recurrence times towards longer and shorter timescales, respectively. We also note that eRO-QPE1 is the most luminous and the most distant QPE discovered to date, and the most extreme in terms of timescales. The outbursts duration and recurrence times in eRO-QPE1 are approximately an order of magnitude longer than in eRO-QPE2. This could simply be an effect of the timescales scaling with black hole mass<sup>17</sup>. We estimated the total stellar mass of the two host galaxies, which is 4-8 times higher in eRO-QPE1 compared to eRO-QPE2. Assuming a standard scaling of the black hole mass with stellar mass (see Methods, ‘The host galaxies of QPEs’), this is broadly in agreement with their different X-ray timing properties. Furthermore, peak soft X-ray luminosities of  $\sim 2 \times 10^{43}$  erg  $s^{-1}$  and  $\sim 10^{42}$  erg  $s^{-1}$ , for eRO-QPE1 and eRO-QPE2 respectively, exclude a stellar-mass black hole origin and their X-ray positions, within uncertainties, suggest a nuclear origin (Extended Data Fig. 1a and 2a).

The optical counterparts of eRO-QPE1 and eRO-QPE2 are local low-mass galaxies with no canonical AGN-like broad emission lines in the optical nor any infrared photometric excess

95 indicating the presence of hot dust (the so-called torus<sup>18</sup>). In this sense they are similar to GSN 069<sup>3</sup>  
and RX J1301.9+2747<sup>4</sup>, whose optical spectra, however, show narrow emission lines with clear  
AGN-driven ionisation<sup>3,4</sup>. Instead, the optical counterpart of eRO-QPE1 is easily classified as a  
passive galaxy from the absence of any significant emission line (Extended Data Fig. 1b) and in  
eRO-QPE2 the strong narrow emission lines observed classify it as a star forming galaxy (Extended  
100 Data Fig. 2b and Methods, ‘The host galaxies of QPEs’). This in turns suggests that the two newly  
discovered galaxies have not been active for at least the last  $\approx 10^3$ - $10^4$  years, assuming narrow-line  
region light-travel timescales<sup>19</sup>. While the number of known QPEs is too low to reach firm  
statistical conclusions, our blind search is inherently designed to sample the QPEs’ host galaxies  
population without bias, as opposed to serendipitous or archival discoveries which relied on the  
source being previously active and known<sup>1,2</sup>. These results hint that perhaps the parent population of  
105 QPE hosts consists more of passive, than active galaxies. The QPEs X-ray spectra in quiescence are  
consistent with an almost featureless accretion disk model<sup>1,2</sup> (see Methods, ‘X-ray spectral  
analysis’), although the inactive nature of the host galaxies of our sources argues against a *pre-*  
*existing* AGN-like accretion system.

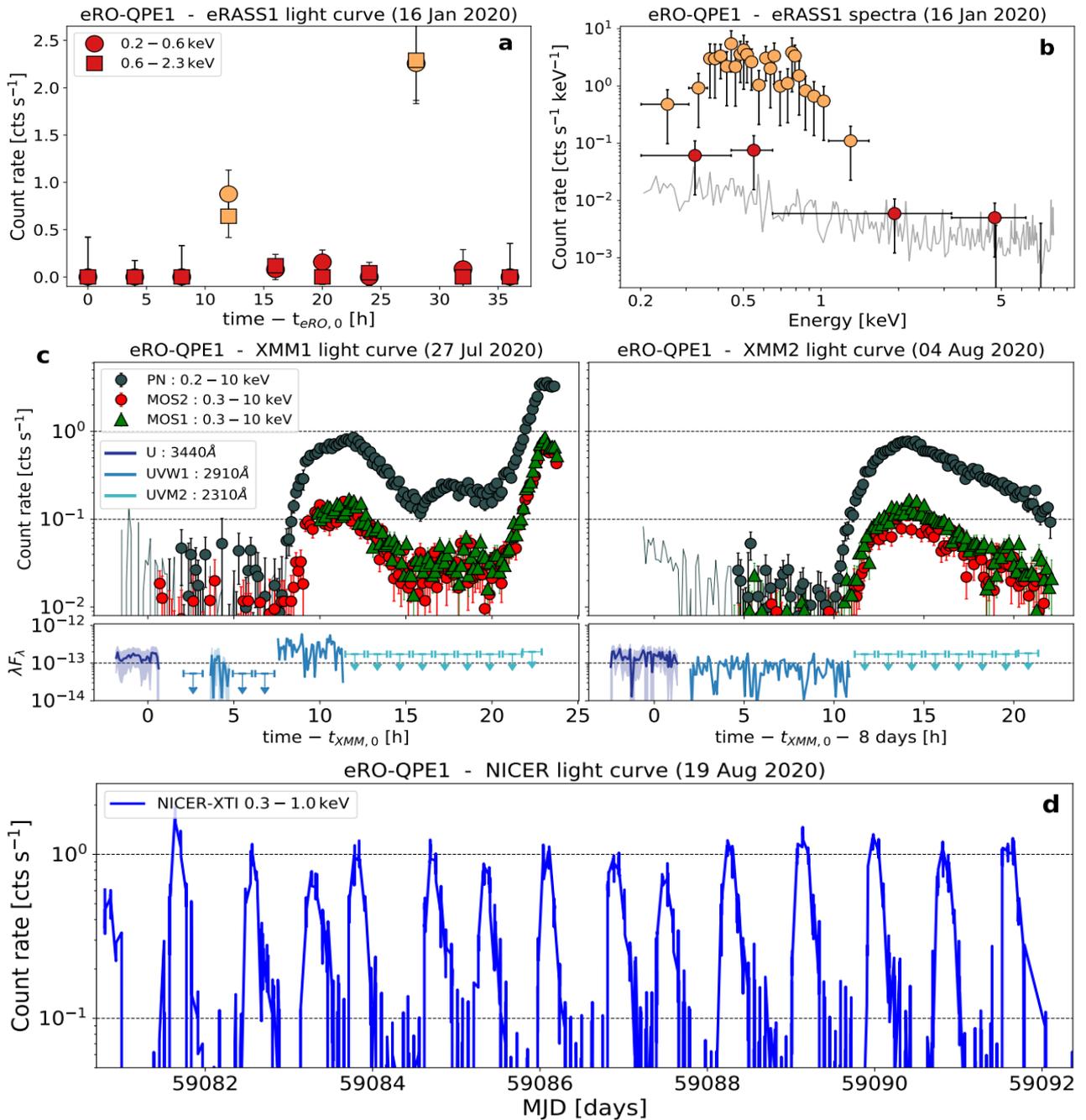
A few scenarios to explain the QPEs have been suggested<sup>1,10</sup>, some based on the presumed active  
110 nature of the QPEs host black holes. These include so-called limit-cycle radiation-pressure  
accretion instabilities (see Methods, ‘On accretion flow instabilities’), proposed for GSN 069<sup>1</sup> based  
on the similarities between its observed properties and two extremely variable stellar-mass black  
holes, namely GRS 1915+105<sup>20,21</sup> and IGR J17091-3624<sup>22</sup>. However, the observed properties of our  
newly discovered QPEs, as well as those of RX J1301.9+2747<sup>2</sup>, are inconsistent with the theoretical  
115 predictions of this scenario<sup>5-9</sup>. In particular, the faster rise and slower decay of eRO-QPE1 would  
imply a thicker flow in the cold and stable phase than in the hot and unstable phase, contrary to  
theory<sup>6</sup>. Moreover, the theory predicts that once the period, the duty cycle and the luminosity  
amplitude are known, only specific values of black hole mass  $M_{\text{BH}}$  and viscosity parameter  $\alpha$  are  
allowed<sup>8</sup>: for eRO-QPE1 (eRO-QPE2) one solution is found for  $M_{\text{BH}} \sim 4 \times 10^6 M_{\odot}$  and  $\alpha \sim 5$  ( $M_{\text{BH}} \sim$   
120  $3 \times 10^6 M_{\odot}$  and  $\alpha \sim 3$ ), therefore for the expected masses<sup>1,2</sup> an unphysically high viscosity parameter  
would be required; alternatively, more reasonable values of  $\alpha \sim 0.1$  and  $\sim 0.01$  would yield very  
small  $M_{\text{BH}} \sim 2.4 \times 10^3 M_{\odot}$  and  $M_{\text{BH}} \sim 60 M_{\odot}$  ( $M_{\text{BH}} \sim 4.3 \times 10^3 M_{\odot}$  and  $M_{\text{BH}} \sim 30 M_{\odot}$ ) for eRO-QPE1  
(eRO-QPE2). Even in this latter scenario and pushing  $\alpha$  as high as  $\sim 0.2$ , the resulting thermal  
timescales for eRO-QPE1 (eRO-QPE2) are  $\tau_{\text{th}} \sim 20\text{s}$  ( $35\text{s}$ ) at  $20 r_{\text{g}}$ , which is orders of magnitude  
125 smaller than the observed QPE timescales (more details in Methods, ‘On accretion flow  
instabilities’).

Extreme or sinusoidal quasi-periodic variability as seen in QPEs is also typically associated with  
compact objects binaries, a scenario which would not require the galactic nuclei to be previously  
130 active, as our new evidence suggests. Drawing a simplistic scenario, we assumed the mass of the  
main body to be in the range  $\sim 10^4$ - $10^7 M_{\odot}$  for both eRO-QPE1 and eRO-QPE2 and computed the  
expected period decrease of a compact binary due to emission of gravitational waves. We inferred  
that an orbiting body with a similar mass, namely a supermassive black-hole binary with a mass  
ratio of order unity<sup>23</sup>, is unlikely given the properties of the observed optical, UV, infrared and X-  
ray emission in QPEs and the lack of evident periodicity and/or strong period decrease therein. If  
135 QPEs are triggered by the presence of a secondary orbiting body, our data suggest its mass ( $M_2$ ) to  
be much smaller than the main body. This is in agreement with at least one proposed scenario for  
the origin of GSN069, for which the average luminosity in a QPE cycle can be reproduced by a  
periodic mass-inflow rate from a white dwarf orbiting the black hole with a highly eccentric orbit<sup>10</sup>.  
Our current data for eRO-QPE1 only exclude  $M_2$  larger than  $\sim 10^6 M_{\odot}$  ( $\sim 10^4 M_{\odot}$ ) for zero (high,  
140 0.9) eccentricity (as a function of the mass of the main body, Extended Data Fig. 7a); instead, for  
eRO-QPE2 we can already argue that only an orbiting  $M_2$  lower than  $\sim 10^4 M_{\odot}$  ( $\sim 10 M_{\odot}$ ) is allowed  
for zero ( $\sim 0.9$ ) eccentricity (Extended Data Fig. 7b). More details are reported in Methods (‘On the  
presence of an orbiting body’).

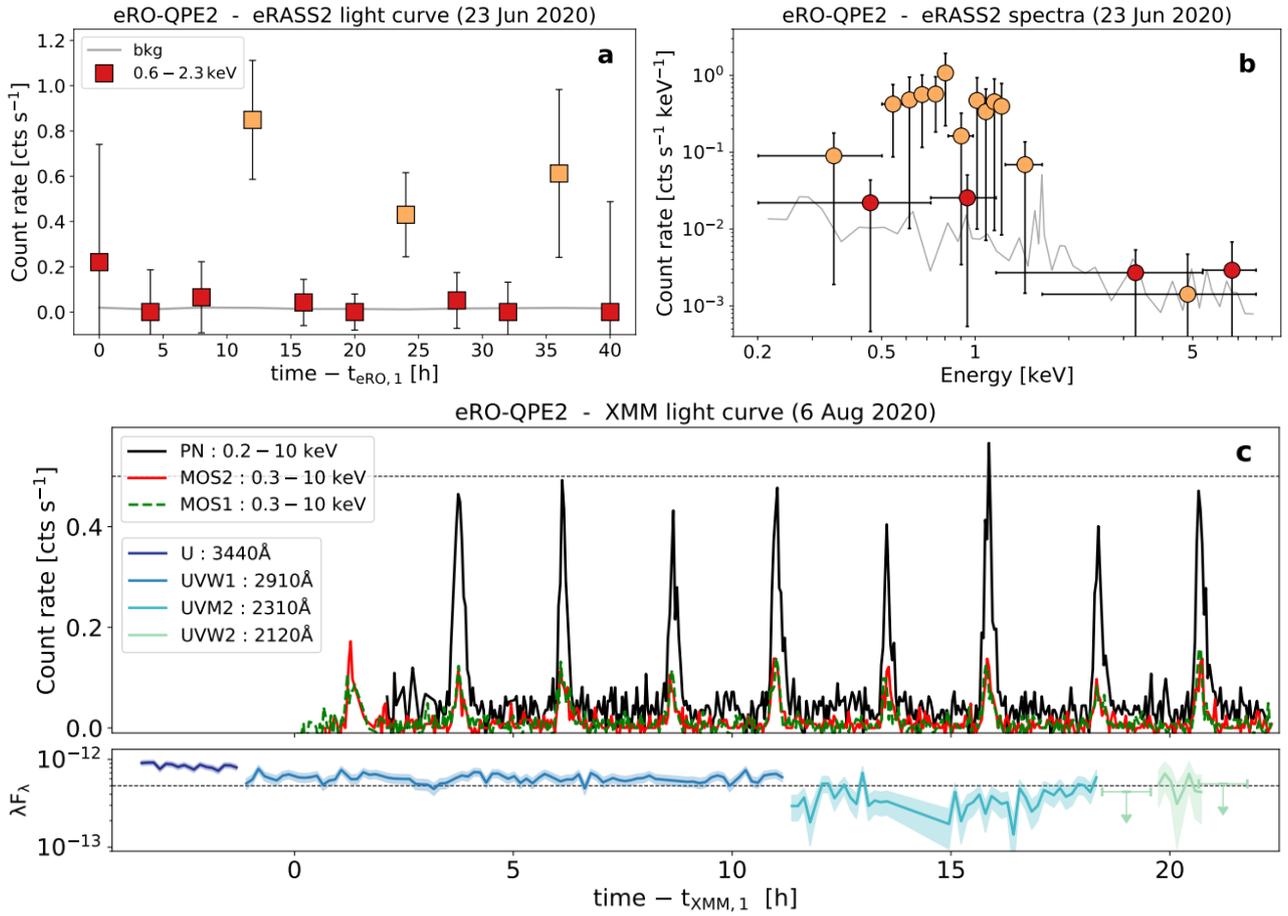
145 Future X-ray observations on longer temporal baselines (months or years) will help to constrain or  
rule out this scenario and to monitor the possible orbital evolution of the system. This picture is also  
reminiscent of a suggested formation channel of extreme mass ratio inspirals<sup>24,25</sup> and it could make  
QPEs their electromagnetic messenger<sup>13,26</sup>. Regardless of their origin, the QPEs seen so far seem to  
be found in relatively low-mass super-massive black-holes ( $\sim 10^5$ - $10^7 M_{\odot}$ ) and finding more will  
150 help us to understand how black holes are activated in low-mass galaxies, a poorly explored mass  
range so far in their co-evolution history<sup>27,28</sup>, which is however crucial for synergies with future  
LISA gravitational waves signals<sup>29</sup>.

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217 **Fig. 1 - The first eROSITA QPE.** **a**, eROSITA light curve in the 0.2-0.6 keV  
 218 energy bands (circles and squares, respectively), with red and orange highlighting faint and bright  
 219 observations, respectively. The start of the light curve is  $t_{eRO,0}$  is MJD~58864.843. **b**, eROSITA X-  
 220 ray spectra of the bright and faint states in orange and red as in **a**. **c**, background subtracted XMM-  
 221 Newton X-ray light curves with 500 s bins for EPIC PN (dark gray), MOS1 (green) and MOS2  
 222 (red) in the energy band shown in the legend. The beginning of both observations was contaminated  
 223 by flares in the background and excluded; the dark grey solid line and contours show the underlying  
 224  $\leq 1$  keV EPIC-PN light curve to give a zeroth-order extrapolation of the rate, excluding the presence  
 225 of obvious soft X-ray eruptions.  $t_{XMM,0}$  corresponds to the start of the cleaned MOS2 exposure in the  
 226 first observation, namely MJD~59057.805. XMM-Newton optical and UV fluxes are shown in the  
 227 lower sub-panels (units of  $\text{erg cm}^{-2} \text{s}^{-1}$ ), with non-detections shown as upper limits. **d**, background  
 228 subtracted NICER-XTI light curve. The mean (and dispersion on) rise-to-decay duration is  $\sim 7.6$   
 229 hours ( $\sim 1.0$  hours) and the peak-to-peak separation is  $\sim 18.5$  hours ( $\sim 2.7$  hours). In all panels  $1\sigma$   
 230 uncertainties are shown, as error bars or shaded regions.



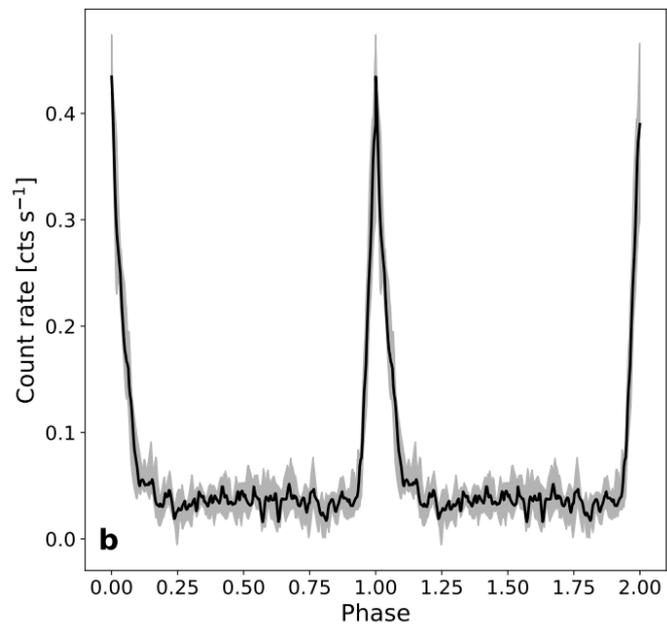
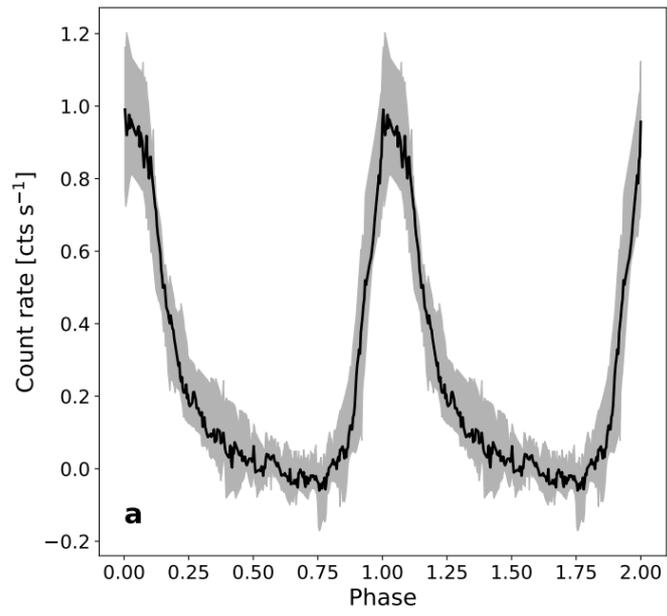
231 **Fig. 2 - The second eROSITA QPE.** a,b same as Fig1a,b but for eRO-QPE2. The start of the  
 232 eROSITA light curve is MJD~59023.191. c, same as the Fig1c but for the XMM-Newton  
 233 observation of eRO-QPE2. t<sub>XMM,1</sub> corresponds to the start of the cleaned MOS1 exposure, namely  
 234 MJD~59067.846. The mean (and related dispersion) of the rise-to-decay duration is ~27 minutes  
 235 (~3 minutes), with a peak-to-peak separation of ~2.4 hours (~5 minutes). In all panels 1σ  
 236 uncertainties are shown, as error bars or shaded regions.

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**Fig. 1 - The first eROSITA QPE.** **a**, eROSITA light curve in the 0.2-0.6 keV and 0.6-2.3 keV energy bands (circles and squares, respectively), with red and orange highlighting faint and bright observations, respectively. The start of the light curve is  $t_{\text{eRO},0}$  is MJD~58864.843. **b**, eROSITA X-ray spectra of the bright and faint states in orange and red as in **a**. **c**, background subtracted XMM-Newton X-ray light curves with 500 s bins for EPIC PN (dark gray), MOS1 (green) and MOS2 (red) in the energy band shown in the legend. The beginning of both observations was contaminated by flares in the background and excluded; the dark grey solid line and contours show the underlying  $\leq 1$  keV EPIC-PN light curve to give a zeroth-order extrapolation of the rate, excluding the presence of obvious soft X-ray eruptions.  $t_{\text{XMM},0}$  corresponds to the start of the cleaned MOS2 exposure in the first observation, namely MJD~59057.805. XMM-Newton optical and UV fluxes are shown in the lower sub-panels (units of  $\text{erg cm}^{-2} \text{s}^{-1}$ ), with non-detections shown as upper limits. **d**, background subtracted NICER-XTI light curve. The mean (and dispersion on) rise-to-decay duration is ~7.6 hours (~1.0 hours) and the peak-to-peak separation is ~18.5 hours (~2.7 hours). In all panels  $1\sigma$  uncertainties are shown, as error bars or shaded regions.

**Fig. 2 - The second eROSITA QPE.** **a,b** same as Fig1a,b but for eRO-QPE2. The start of the eROSITA light curve is MJD~59023.191. **c**, same as the Fig1c but for the XMM-Newton observation of eRO-QPE2.  $t_{\text{XMM},1}$  corresponds to the start of the cleaned MOS1 exposure, namely MJD~59067.846. The mean (and related dispersion) of the rise-to-decay duration is ~27 minutes (~3 minutes), with a peak-to-peak separation of ~2.4 hours (~5 minutes). In all panels  $1\sigma$  uncertainties are shown, as error bars or shaded regions.

**Fig. 3 – Phase-folded light curves.** Median light curve profile (with related 16<sup>th</sup> and 84<sup>th</sup> percentile contours) for eRO-QPE1 (**a**) and eRO-QPE2 (**b**), folded at the eruptions peaks (see Methods).



## Methods

### 240 **Blind search for QPEs with eROSITA**

eROSITA<sup>16</sup> is the main instrument aboard the Spectrum-Roentgen-Gamma (SRG) mission (R. Sunyaev et al., in preparation), which was launched on 13 July 2019. On 13 December 2019 it started the first of eight all-sky surveys (eRASS1-8), each completed in six months, observing in the 0.2-8 keV band. In each survey, as the field of view moves every point of the sky is observed for  
245 ~40 seconds every ~4 hours with the number of times (typically six) varying with the location in the sky, increasing towards high ecliptic latitudes. Our search for QPE candidates starts with a systematic screening of all eROSITA light curves, produced for each detected source on a weekly basis by the eROSITA Science Analysis Software (eSASS; H. Brunner et al., in preparation). Light curves are binned to yield one data point for each 4-hour revolution (called an ‘eROday’). A light  
250 curve generated by the eSASS pipeline will trigger a ‘QPE alert’ if it shows two or more high-count states with (at least) one low-count state in between (see Fig. 1a and 2a as examples) in any of its standard energy bands (0.2-0.6, 0.6-2.3, 2.3-5.0 keV). As thresholds, we fixed a relative count rate ratio (including uncertainties) of 5, if both high and low states are detected, or 3, if the low-count state is consistent with the background. Since neither the survey scans nor QPEs are strictly  
255 periodic, every eRASS can be treated as an independent sky to find new candidates. This produces a census of X-ray sources varying on hours timescales for each eRASS, albeit only for the specific intermittent pattern described above. Unsurprisingly, the vast majority of the automatically generated alerts are produced by Galactic sources (mainly flaring coronally active stars), but we can filter them out by finding the multi-wavelength counterpart associated to every X-ray source (M.Sa.  
260 et al., in preparation). Good QPE candidates are then selected screening the handful of alerts with a secure or possible extra-galactic counterpart. Thanks to this process, we identified the two best eROSITA QPE candidates which were worth immediate follow-up, promptly obtained with both XMM-Newton and, in one case, NICER. Given the success of our initial search over the first nine months of the survey, we are confident that we can detect up to ~3-4 good eROSITA QPE  
265 candidates every year. Therefore, by the end of the last eROSITA all-sky survey in December 2023 this search may provide a sample of up to ~10-15 QPEs.

*The two new eROSITA QPEs.* The first QPE, here named eRO-QPE1, is eRASSU J023147.2-102010 located at the astrometrically-corrected X-ray position of  $RA_{J2000}, DEC_{J2000}=(02:31:47.26, -10:20:10.31)$ , with a total  $1\sigma$  positional uncertainty of ~2.1". It was observed ten times between 16  
270 and 18 January 2020 during eRASS1 with 339 s of total exposure. Using the Bayesian cross-matching algorithm NWAY<sup>30</sup> we associated eRO-QPE1 with the galaxy 2MASS 02314715-1020112 at  $RA_{J2000}, DEC_{J2000}=(02:31:47.15, -10:20:11.22)$ . The second QPE, here named eRO-QPE2, is eRASSU J023448.9-441931 located at the astrometrically-corrected X-ray position of  $RA_{J2000}, DEC_{J2000}=(02:34:48.97, -44:19:31.65)$ , with a total positional uncertainty of ~3.2". It was observed  
275 11 times between 23 and 24 June 2020 during eRASS2. It was associated via the same method<sup>30</sup> with 2MASX J02344872-4419325, a galaxy at  $RA_{J2000}, DEC_{J2000}=(02:34:48.69, -44:19:32.72)$ . Both galaxies are in the DESI Legacy Imaging Surveys<sup>31</sup> DR8 footprint (Extended Data Fig. 1a and 2a). X-ray XMM-Newton positions were corrected with the ‘eposcorr’ task cross-correlating the sources in the X-ray image with external optical and infrared catalogs. The counterparts of the QPE itself  
280 was excluded from the cross-correlation to obtain a more unbiased estimate of the possible offset from the nucleus. The XMM-Newton X-ray positions are consistent with the nuclei of these galaxies. We took optical spectra of both galaxies with the Southern African Large Telescope (SALT<sup>32</sup>) and measured spectroscopic redshifts of 0.0505 and 0.0175, for eRO-QPE1 and eRO-QPE2, respectively (Extended Data Fig. 1b and 2b). More details are show in the following sections  
285 of Methods (‘Data reduction’ and ‘The host galaxies of QPEs’).

*Previous X-ray activity.* eRO-QPE1 has not previously been detected in X-rays, although upper limits can be obtained from the XMM-Newton upper limits server for ROSAT<sup>49</sup>, both from the

survey and a pointed observation (taken in 1991 and 1992, with  $\sim 270$  and  $\sim 5300$  seconds, respectively), and the XMM-Newton Slew Survey<sup>50</sup> (taken in 2004, 2007, 2008 and 2017, all between  $\sim 3$ -8 seconds of exposure). The ROSAT pointed observation puts a stringent upper limit at  $\leq 3.8 \times 10^{-14}$  cgs in the 0.2-2.0 keV band. However, given the very short exposures compared with the timescales of eRO-QPE1, we can not rule out that QPEs were already ongoing and that all previous missions caught eRO-QPE1 in a faint state. Like eRO-QPE1, eRO-QPE2 has not been previously detected in X-rays. Upper limits were again computed for ROSAT (taken in 1990,  $\sim 480$  seconds of exposure) and the XMM-Newton Slew survey (taken in 2004, 2008, 2012 and 2013, all between  $\sim 4$ -8 seconds). The most stringent upper limit, at  $\leq 8.8 \times 10^{-14}$  cgs in the 0.2-2.0 keV band, comes from ROSAT. It is slightly below the flux observed by XMM-Newton in quiescence in the same band (Extended Data Fig. 4), perhaps indicating that the QPE behaviour only started more recently. For both QPE sources however, the ROSAT and Slew exposures are too shorter than the evolving timescales (the QPE quasi-period and its dispersion), hence they do not provide meaningful constraints on the start of the QPE behavior.

### Data reduction

In this Section we report details of the processing of the complete data-set. We show a summary of the observations in Extended Data Table 1.

*eROSITA*. Members of the German eROSITA consortium (eROSITA-DE) have full and immediate access to survey data at Galactic longitudes  $180^\circ < l < 360^\circ$ . These data were processed using eSASS v946 (H. Brunner et al. in preparation). For eRO-QPE1 (eRO-QPE2), photons were extracted choosing a circular aperture of radius 80" (67"), while background counts were extracted from an annulus (off-centered circle) of inner and outer radii 178" (382") and 996", respectively, excluding all the other sources detected within the area. eRO-QPE1 was detected with a detection likelihood of 440 and a total number of 119 counts in the 0.2-5.0 keV band. eRO-QPE2 was detected with a detection likelihood of 125 and a total number of 48 counts in the 0.2-5.0 keV band.

*XMM-Newton*. XMM-Newton data from EPIC MOS1-2<sup>33</sup> and EPIC-PN<sup>34</sup> cameras and the Optical Monitor (OM<sup>35</sup>) were processed using standard tools (SAS v. 18.0.0 and HEASoft v. 6.25) and procedures. Event files from EPIC cameras were filtered for flaring particle background. Source (background) regions were extracted within a circle of 38" and 34" in eRO-QPE1 and eRO-QPE2, respectively, centered on the source (in a source-free region). eRO-QPE1 was consecutively observed three times with the U filter, then seven times with UVW1 and nine (eight) times with the UVM2 in the first (second) XMM-Newton observation, each exposure  $\sim 4400$  s long. The source was detected only in the U and UVW1 with mean magnitudes  $\sim 19.9$  and  $\sim 20.3$  in both XMM-Newton observations (OM light curves in Fig 1c). eRO-QPE2 was consecutively observed twice with the U filter, then ten times with UVW1, six with UVM2 and three with UVW2 with all exposures being 4400s. It was almost always detected in all filters with mean magnitudes of  $\sim 17.4$ ,  $\sim 17.5$ ,  $\sim 18.0$ , and  $\sim 18.1$ , for U, UVW1, UVM2 and UVW2 filter, respectively (OM light curves in Fig 2c). eRO-QPE2 was flagged as extended in the U, UVW1 and UVM2 filters, therefore the reported absolute magnitudes include at least some contamination from the host galaxy.

*NICER*. NICER's X-ray Timing Instrument (XTI<sup>36,37</sup>) onboard the ISS observed eRO-QPE1 between 17 August 2020 and 31 August 2020. Beginning late on 19 August, high-cadence observations were performed during almost every ISS orbit, which is roughly 93 minutes. All the data were processed using the standard NICER Data Analysis Software (NICERDAS) task 'nicerl2'. Good time intervals (GTIs) were chosen with standard defaults, yielding  $\sim 186$  ks of exposure time. We further divided the GTIs into intervals of 128 s, and on this basis we extracted the spectra and applied the '3C50' model (R.R. et al., submitted) to determine the background spectra. The light curve for eRO-QPE1 in soft X-rays (Fig. 1d) was determined by integrating the

background-subtracted spectrum for each 128-s GTI over the range 0.3-1.0 keV. More detailed spectral analyses of these data will be discussed in a follow-up paper.

340 *SALT*. Optical spectra of eRO-QPE1 and eRO-QPE2 were obtained using the Robert Stobie Spectrograph (RSS<sup>38</sup>) on the Southern African Large Telescope (SALT<sup>32</sup>) on the nights of 2020 September 24 and 8, respectively. The PG900 VPH grating was used to obtain pairs of exposures (900 s and 500 s, respectively) at different grating angles, allowing for a total wavelength coverage of 3500-7400Å. The spectra were reduced using the PySALT package, a PyRAF-based software package for SALT data reductions<sup>39</sup>, which includes gain and amplifier cross-talk corrections, bias subtraction, amplifier mosaicing, and cosmetic corrections. The individual spectra were then  
345 extracted using standard IRAF procedures, wavelength calibration (with a calibration lamp exposure taken immediately after the science spectra), background subtraction and extraction of 1D spectra. We could only obtain relative flux calibrations, from observing spectrophotometric standards in twilight, due to the SALT design, which has a time-varying, asymmetric and underfilled entrance pupil<sup>40</sup>.

### 350 **X-ray spectral analysis**

In this work, X-ray spectral analysis was performed using v3.4.2 of the Bayesian X-ray Analysis software (BXA<sup>41</sup>), which connects a nested sampling algorithm (UltraNest<sup>42</sup>; J.B. in preparation) with a fitting environment. For the latter, we used XSPEC v12.10.1<sup>43</sup> with its Python oriented interface pyXSPEC. eROSITA source plus background spectra were fit including a model  
355 component for the background, which was determined via a principal component analysis (PCA) from a large sample of eROSITA background spectra<sup>44</sup> (J.B. et al., in preparation). XMM-Newton EPIC-PN spectra were instead fit using wstat, namely XSPEC implementation of the Cash statistic<sup>45</sup>, given the good counts statistics in both source and background spectra. We quote, unless otherwise states, median values with the related 16th and 84th percentiles and upper limits at  $1\sigma$ .  
360 Results are also reported in Extended Data Table 2 and 3.

*eRO-QPE1*. For eRO-QPE1 both eROSITA and XMM-Newton EPIC-PN spectra were fit with a simple absorbed black-body (using the models tbabs<sup>46</sup> and zbody) or accretion disk (tbabs and diskbb<sup>47</sup>), with absorption frozen at the Galactic column density of  $N_{\text{H}} \sim 2.23 \times 10^{20} \text{ cm}^{-2}$ , as reported by the HI4PI Collaboration<sup>48</sup>. For eROSITA, we jointly extracted and analysed spectra of the faint  
365 states (red points in Fig1a) and, separately, of the two bright states observed in eRASS1 (orange points in Fig1a). In the eROSITA bright states the temperature, in terms of  $k_{\text{B}}T$  in eV, is  $138_{131}^{146} \text{ eV}$  and  $180_{168}^{195} \text{ eV}$ , using zbody and diskbb as source model, respectively. The related unabsorbed rest-frame 0.5-2.0 keV fluxes are  $1.6_{1.4}^{1.8} \times 10^{-12} \text{ cgs}$  and  $1.5_{1.4}^{1.7} \times 10^{-12} \text{ cgs}$ , respectively. The eROSITA spectrum of the faint states combined is consistent with background, with the temperature and  
370 unabsorbed rest-frame 0.5-2.0 keV flux constrained to be  $\leq 124 \text{ eV}$  ( $\leq 160 \text{ eV}$ ) and  $\leq 3.5 \times 10^{-14} \text{ cgs}$  ( $\leq 3.4 \times 10^{-14} \text{ cgs}$ ) for zbody (diskbb). We also analysed the observations of eRO-QPE1 obtained six months later during eRASS2, which triggered our QPE search again: two bright states were observed separated by several faint ones, with fluxes consistent with eRASS1.

We performed time-resolved X-ray spectral analysis on XMM-Newton data, extracting a spectrum  
375 in each 500s time bin of the EPIC-PN light curve, with the exception of the quiescence spectrum, which was extracted and analysed combining all the related time bins of both observations (i.e. before  $t \sim 26500 \text{ s}$  in eRO-QPE1-XMM1 and before  $t \sim 35788 \text{ s}$  in eRO-QPE1-XMM2, with times as defined in Fig1c). Fit results obtained using XMM-Newton EPIC-PN spectra with diskbb as the source model component are shown in Extended Data Fig. 3. Furthermore, we show for  
380 visualization three EPIC-PN spectra and related best-fit models (Extended Data Fig. 5a) corresponding to the quiescence phase and the peak of both XMM-Newton observations. A more thorough X-ray spectral analysis with other models and additional components for the bright phase will be presented in future work.

385 *eRO-QPE2*. For eRO-QPE2 eROSITA's faint and bright phases were also separately combined and analysed (Fig 2a,b). The faint state as observed by eROSITA is consistent with background. The temperature and normalization of the source can not be constrained, thus we only quote an upper limit for the unabsorbed rest-frame 0.5-2.0 keV flux of  $\leq 1.9 \times 10^{-14}$  cgs ( $\leq 5.7 \times 10^{-14}$  cgs) using zbody (diskbb). The spectrum of the eROSITA bright states constrains the temperature to  $164_{149}^{182}$  eV and at 209<sub>185</sub><sup>241</sup> eV, using zbody and diskbb as source model, respectively. The related unabsorbed rest-  
390 frame 0.5-2.0 keV fluxes are  $1.4_{1.2}^{1.8} \times 10^{-12}$  cgs and  $1.5_{1.2}^{1.8} \times 10^{-12}$  cgs, respectively. The triggering eROSITA observation was obtained during eRASS2, although a single bright state (thus not satisfying our trigger criterion) was also detected in eRASS1 with the same flux level. For eRO-QPE2, in addition to the Galactic column density ( $N_{\text{H}} \sim 1.66 \times 10^{20}$  cm<sup>-2</sup> [48]) we included an absorption component at the redshift of the host galaxy (i.e. with the models tbabs, ztbabs, and zbody or diskbb). This excess absorption was inferred to be present based on the XMM-Newton spectrum (see below).  
395

For XMM-Newton, we performed time-resolved X-ray spectral analysis for each 150 s time bin of the EPIC-PN light curve. The absorption in addition to the Galactic value was first fitted in the XMM-Newton quiescence spectrum, which was extracted combining all the low states in the  
400 XMM-Newton light curve (Fig. 2c and Extended Data Fig. 4). The fit yielded a  $N_{\text{H}} = 0.35_{0.30}^{0.40} \times 10^{22}$  cm<sup>-2</sup>. In all other observations, including all eROSITA spectra and the rises, peaks and decays in the XMM-Newton light curve, the additional  $N_{\text{H}}$  was left free to vary between the 10th and 90th percentile of the fitted posterior distribution of the quiescent spectrum. Under the assumption that absorption did not vary throughout the observation, this ensures that no spurious effects is imprinted  
405 on the fit temperature and normalisations due to degeneracies with  $N_{\text{H}}$ ; at the same time, in this way parameters are marginalised over a reasonable range in  $N_{\text{H}}$ . Freezing the value instead would artificially narrow the uncertainties on the temperature and normalisations. Fit results obtained with diskbb as the source model are shown in Extended Data Fig. 4. Furthermore, we show for visualization the EPIC-PN spectra and best-fit models of the quiescence and peak phases (Extended  
410 Data Fig. 5b). Similar results are obtained using zbody as the source model.

### Timing analysis

In Fig. 3 we show the median (with related 16<sup>th</sup> and 84<sup>th</sup> percentile contours) light curve profiles obtained by folding the light curve at the eruptions peaks. First, a random representative burst is selected and cross-correlated with the whole light curve. The peaks of this cross-correlation identify  
415 the times when the phase is zero. Data are then folded at these phase zero times to obtain a template median profile, which is then used to repeat the same operation and yield Fig. 3. A phase bin of  $\sim 0.1$  corresponds to  $\sim 6600$ s and  $\sim 820$ s for eRO-QPE1 and eRO-QPE2, respectively. Moreover, XMM-Newton and NICER light curve profiles were fit with UltraNest<sup>42</sup>. Motivated by the strong asymmetry in eRO-QPE1 (Fig 1c,d and Fig 3a), we adopted a model with Gaussian rise and an exponential decay, a generic model often adopted for transients<sup>51</sup>. eRO-QPE2, on the other hand,  
420 can be fit with a simple Gaussian profile (Fig. 3b), possibly due to the much shorter timescales. Here we simply highlight the most evident results of timing analysis, while a more in depth study of the variability properties of QPEs is deferred to future work. Here the modeling allows us to determine mean values for the QPEs duration and recurrence time, which were used for comparison  
425 with models of accretion instabilities (see 'On accretion flow instabilities') and compact object binaries (see 'On the presence of an orbiting body'). The mean rise-to-decay duration for eRO-QPE1, as observed from the NICER light curve (Fig. 1d), is  $\sim 7.6$  hours (dispersion of  $\sim 1.0$  hours), while the mean peak-to-peak separation is  $\sim 18.5$  hours (dispersion of  $\sim 2.7$  hours). The related duty-cycle (here computed simply as mean duration over mean separation) is  $\sim 41\%$ . Conversely, eRO-QPE2 shows much narrower and more frequent eruptions (see Fig. 2c): the mean the rise-to-decay  
430

duration is  $\sim 27$  minutes (dispersion of  $\sim 3$  minutes), with a mean peak-to-peak separation of  $\sim 2.4$  hours (dispersion of  $\sim 5$  minutes) and a duty-cycle of  $\sim 19\%$ .

### The host galaxies of QPEs

435 Very little was known on both galaxies from published multi-wavelength catalogs, except for WISE  
infrared monitoring indicating a quite stable W1~W2 emission, typical of inactive galactic nuclei,  
for the last few years. Most of our knowledge is based on optical spectra taken with SALT after the  
X-ray discovery. The optical counterpart of eRO-QPE1 is classified as a passive galaxy from the  
absence of any significant emission line (Extended Data Fig. 1b), whereas eRO-QPE2 shows very  
440 strong and narrow  $[\text{O}_{\text{II}}]$ ,  $\text{H}\beta$ ,  $[\text{O}_{\text{III}}]$ ,  $\text{H}\alpha$ ,  $[\text{N}_{\text{II}}]$  and  $[\text{S}_{\text{II}}]$  in emission (Extended Data Fig. 2b). The high  
 $[\text{O}_{\text{II}}]/[\text{O}_{\text{III}}]$  ratio and  $\text{H}\beta$  being as strong and  $[\text{O}_{\text{III}}]$  are already strongly indicative that star forming  
processes are the dominant ionization mechanism<sup>52</sup>. We computed the flux ratios  $\log([\text{O}_{\text{III}}]/\text{H}\beta)=-$   
 $0.05$ ,  $\log([\text{O}_{\text{II}}]/\text{H}\beta)=0.44$  and  $\log([\text{N}_{\text{II}}]/\text{H}\alpha)=-0.68$ , as well as  $\log \text{EW}_{\text{OII}}=2.56$  and  $D_n(4000)=1.26$ ,  
where  $D_n(4000)$  is the ratio of the continuum level after and before the  $4000\text{\AA}$  break<sup>53</sup>. Using  
445 standard line diagnostics plots<sup>54</sup> we can confirm that indeed eRO-QPE2 can be classified as star  
forming. Spectroscopic classification of future QPEs will be crucial to confirm whether their host  
galaxies are indeed preferentially inactive, as our pilot study suggests, or not. A first census in a  
statistically significant sample may bring new insights as has been the case for other transients, such  
as Tidal Disruption Events (TDEs)<sup>55-58</sup>.

A preliminary analysis of the properties of QPEs' host galaxies was performed by fitting the optical  
450 spectra (Extended Data Fig. 1b and 2b) with Firefly<sup>59,60</sup>. We first re-normalized the flux of the  
optical spectra using the most recent g-band and r-band archival magnitudes, since SALT spectra  
are not calibrated to absolute values<sup>40</sup>. For eRO-QPE1, gri-band photometry ( $g=18.7\pm 0.06$ ,  
 $r=18.0\pm 0.05$ ,  $i=17.8\pm 0.05$  mag) was taken on July 30<sup>th</sup> 2020 with the Rapid Response Robotic  
Telescope at Fan Mountain Observatory, indicating that the source did not change significantly with  
455 respect to archival photometry<sup>61</sup>. The total stellar masses inferred with Firefly from the optical  
spectra are  $M_*\sim 3.8^{+0.4}_{-1.9}\times 10^9 M_\odot$  and  $\sim 1.01^{+0.01}_{-0.50}\times 10^9 M_\odot$  for eRO-QPE1 and eRO-QPE2, respectively.  
Systematic errors and degeneracy due to the use of different stellar population models<sup>62</sup> would push  
 $M_*$  to higher values for eRO-QPE1 ( $\sim 4.8\times 10^9 M_\odot$ ) and lower values for eRO-QPE2 ( $\sim 0.6\times 10^9 M_\odot$ ),  
enhancing their relative difference. Firefly also yields an estimate of the age of the stellar  
460 population and the star formation rate (SFR), although for medium and low signal-to-noise ratios  
these estimates are more prone to biases<sup>59</sup>. For eRO-QPE2, the mean signal-to-noise ratio ( $\sim 23$ ) is  
high enough to yield a fairly reliable  $\text{SFR}\sim 0.078^{+0.001}_{-0.066} M_\odot/\text{yr}$ , which is also consistent within  
uncertainties with the SFR that can be estimated from the  $[\text{O}_{\text{II}}]$  and  $\text{H}\alpha$  luminosities<sup>63,64</sup>. For eRO-  
QPE1 the mean signal-to-noise ratio ( $\sim 8$ ) is lower and no reliable estimate of the SFR was obtained.  
465 We therefore inferred an upper limit of  $\sim 0.01 M_\odot/\text{yr}$  from the absence of significant narrow  
emission lines<sup>63,64</sup>. We report in Extended Data Fig. 6 the  $M_*$ -SFR plane with our two newly  
discovered QPEs, together with normal galaxies, and hosts of known TDEs<sup>57</sup> and CLAGN<sup>65</sup>, all  
taken below  $z<0.1$  and within the Sloan Digital Sky Survey MPA-JHU DR7 catalog<sup>66</sup>. Evidence is  
mounting that both TDEs<sup>57,67</sup> and CLAGN<sup>65</sup> might be over represented in galaxies in the so-called  
470 'green valley', perhaps indicating that they are activated in specific periods of galaxy co-evolution  
with their central black holes. For QPEs, a statistically meaningful sample still needs to be built  
before reaching any conclusion.

We have estimated that the host galaxy of eRO-QPE1 is more massive than that of eRO-QPE2. We  
475 here refrain from quoting absolute values for black hole masses using their scaling relations with  
the host galaxies properties, since our stellar masses are lower than the ones used to calibrate  
them<sup>68</sup>. However, it is worth mentioning that the relative ratio of  $\sim 4-8$  in stellar masses, between  
eRO-QPE1 and eRO-QPE2, would propagate to a black hole mass ratio of the order of  $\sim 10$  [68].  
This is in line with the X-ray timing properties in eRO-QPE1 and eRO-QPE2, since their peak-to-  
peak separation and rise-to-decay duration scale roughly by the same amount. Finally, X-ray

480 emission from eRO-QPE1 and eRO-QPE2 was observed to be positionally consistent with the galaxy nucleus for both objects (Extended Data Fig. 1a and 2a; Methods, ‘The two new eROSITA QPEs’). If a future QPE is found in a more nearby galaxy we can aim to constrain more precisely the X-ray position with respect to the galactic nucleus. This will allow us to determine conclusively whether or not these phenomena are nuclear.

#### 485 **On accretion flow instabilities**

Accretion disks<sup>69</sup> with an accretion rate such that radiation-pressure dominates in the inner flow are thought to be subject to thermal-viscous instabilities<sup>70</sup>. The net result of these instabilities is that the luminosity is predicted to oscillate<sup>5-8</sup> with timescales and amplitude proportional to the black-hole mass and bolometric luminosity<sup>71,72</sup>. The predicted light curves profiles show first a stable and slow rise in luminosity, as both temperature and surface density increase while matter is slowly accumulated. Thereafter a sharp luminosity burst is produced by a runaway increase (decrease) in temperature (surface density) propagating outwards within the unstable region. Finally, the inner flow, devoid of the matter supply, cools down rapidly and cycles back to the initial stable state with low temperature and density. Both heating and cooling fronts propagate following thermal timescales<sup>6</sup>, where  $\tau_{\text{th}} \sim \alpha^{-1} (GM_{\text{BH}}/R^3)^{-1/2}$ . These so-called limit-cycle or heartbeat instabilities have been successfully applied to a few accreting sources across all mass scales, for instance to the stellar-mass black holes GRS 1915+105<sup>20,21,73</sup>, IGR J17091-3624<sup>22</sup> and 4XMM J111816.0-324910<sup>74</sup> and to super-massive black holes in a statistical fashion<sup>72,73</sup>. The similarity of their timing properties with QPEs in GSN069 is tantalizing and naturally led to the proposed connection with limit-cycle instabilities for that object. In particular, the symmetry of the eruptions in GSN069 was compared to the fast heating and cooling phases of the instability<sup>1</sup>, both following similar  $\tau_{\text{th}}$  under the assumption of invariant  $\alpha$  across the two phases<sup>75</sup>. The lack of a slow rise before the eruptions in QPEs, predicted by the instability models, could be due to our limited coverage of the full disk temperature profile in the soft X-ray band.

505 With the two newly discovered QPEs we can now argue against at least this type of accretion disk instability as the origin of QPEs. Specifically, the strong asymmetric nature of the eruptions in eRO-QPE1, which show a faster rise and a much slower decay (Fig. 3a), argues against this interpretation. Qualitatively, our data would suggest that QPEs are not related to  $\tau_{\text{th}}$ , since  $\alpha$  is not expected to change between the hot and cold phases in AGN<sup>75</sup>. Moreover, if instead it is the front propagation timescales, following  $\tau_{\text{front}} \sim (H/R)^{-1} \tau_{\text{th}}$ , or viscous timescales, following  $\tau_{\text{visc}} \sim (H/R)^{-2} \tau_{\text{th}}$ , that regulates the rise (decay) in the cold (hot) phase, it would imply a thicker flow in the cold and stable phase than in the hot and unstable phase. This runs contrary to the theoretical expectation that unstable flows should be thicker<sup>6</sup>. The limit-cycle oscillation theory further predicts that once the period, duty cycle and luminosity amplitude are known and a viscosity prescription for the accretion flow is adopted, there are only specific values of  $M_{\text{BH}}$  and  $\alpha$  that unstable sources are allowed to follow<sup>8</sup>. Here we adopt for eRO-QPE1 (eRO-QPE2) a peak-to-peak period  $T_{\text{pp}}=18.5$  h (2.4 h), an amplitude  $A \sim 294$  ( $\sim 11$ ) and a duty-cycle  $D=41\%$  (19%). The amplitude  $A$  is the ratio of the disk luminosity (computed within the 0.001-100 keV range) for peak and quiescence, taken as proxy of the maximum and minimum bolometric luminosity, while  $D$  is here defined as the ratio of the flare duration (rise-to-decay  $T_{\text{rd}}$ ) and the period  $T_{\text{pp}}$ . We begin by adopting a standard viscosity prescription, with the average stress between the annuli proportional to the gas plus radiation pressure  $P_{\text{tot}}$  [69]. The allowed  $M_{\text{BH}}$  and  $\alpha$  values for eRO-QPE1 (eRO-QPE2) are  $M_{\text{BH}} \sim 4 \times 10^6 M_{\odot}$  and  $\alpha \sim 5$  ( $M_{\text{BH}} \sim 3 \times 10^6 M_{\odot}$  and  $\alpha \sim 3$ ), therefore an unphysically high viscosity parameter would be required. Considering alternative viscosity prescriptions<sup>5,8</sup>, for eRO-QPE1 (eRO-QPE2) a more reasonable  $\alpha \sim 0.1$  or  $\sim 0.01$  would correspond to allowed  $M_{\text{BH}} \sim 2.4 \times 10^3 M_{\odot}$  or  $M_{\text{BH}} \sim 60 M_{\odot}$  ( $M_{\text{BH}} \sim 4.3 \times 10^3 M_{\odot}$  or  $M_{\text{BH}} \sim 30 M_{\odot}$ ), respectively. The above combinations are either unphysical or very unlikely. Adopting  $\alpha \sim 0.2$  and alternative viscosity prescriptions eRO-QPE1 (eRO-QPE2) would yield an intermediate-mass black hole (IMBH) at  $M_{\text{BH}} \sim 0.9 \times 10^4 M_{\odot}$  ( $M_{\text{BH}} \sim 1.6 \times 10^4 M_{\odot}$ ) accreting at  $\sim 0.1$  ( $\sim 0.3$ ) Eddington in quiescence and at  $\sim 30$  ( $\sim 3$ ) Eddington at the peak. However, this IMBH

530 scenario would not account for the opposite asymmetry shown by eRO-QPE1 compared to the  
theoretical predictions, nor would the resulting thermal timescales be self-consistent for either of the  
two: for eRO-QPE1 (eRO-QPE2)  $\tau_{\text{th}} \sim 20\text{s}$  ( $35\text{s}$ ) at  $20 r_g$  adopting  $M_{\text{BH}} \sim 0.9 \times 10^4 M_{\odot}$  ( $M_{\text{BH}} \sim 1.6 \times 10^4$   
535  $M_{\odot}$ ), which is orders of magnitude smaller than the observed QPE durations, and the rise-to-peak  
times would be only reconciled with  $\tau_{\text{th}}$  at  $\sim 780 r_g$  ( $\sim 250 r_g$ ). Analogous results can be obtained  
using the observed properties of RX J1301.9+2747<sup>2</sup>, adopting  $T_{\text{pp}} \sim 20\text{ ks}$  (or the second period  
 $T_{\text{pp}} \sim 13\text{ ks}$ ),  $D=6\%$  ( $9\%$ ) and  $A \sim 9.4$ , the latter obtained taking the ratio of the quoted quiescence and  
peak 0.3-2.0 keV flux as proxy for a bolometric luminosity ratio: adopting<sup>2</sup>  $\alpha \sim 0.15$  the allowed  
black hole mass is  $\sim 2.2 \times 10^4 M_{\odot}$  ( $\sim 1.5 \times 10^4 M_{\odot}$ ), much lower than the quoted<sup>2,76</sup>  $\sim 0.8-2.8 \times 10^6 M_{\odot}$ .

540 When a given source is in a ‘sweet-spot’ regime in mass accretion rate, some more recent modified  
accretion disks viscosity prescriptions predict the presence of a narrow unstable zone placed within  
an inner inefficient advection-dominated flow and an outer standard geometrically-thin and stable  
flow<sup>9</sup>. This model would reduce the propagation timescales by a factor  $\sim dR/R$ , where  $dR$  is the  
radial extent of the unstable zone at a distance  $R$  from the black hole, which may help reconcile the  
545 model with the dramatic and fast variability observed in CLAGN<sup>77</sup>. This would not, however,  
change the inconsistency with the asymmetric shape of the newly observed QPEs, nor was it  
successful in modeling all the observables in GSN 069<sup>9</sup>. In summary, our data for both our newly-  
detected QPEs are inconsistent with published models for radiation pressure instability<sup>5-9</sup>. The role  
of more complex, or exotic phenomenology<sup>9</sup> should be further explored.

550 We also note that a fast-rise exponential-decay profile, like the one in eRO-QPE1, can be naturally  
produced by ionization instability models which are used for some bursting stellar-mass accreting  
compact objects<sup>78</sup>. To our knowledge there is no evidence so far of such instabilities taking place in  
AGN<sup>79</sup>. In addition, the predicted timescales are many orders of magnitude longer than QPEs for  
both AGN<sup>79-81</sup> and IMBH masses<sup>82</sup>.

555 Finally, we discuss disk warping and tearing induced by Lense-Thirring precession<sup>83,84</sup>, which has  
been recently qualitatively compared also to QPE sources<sup>85</sup>. In this work we presented new  
evidence of QPEs being observed in previously inactive galaxies, therefore the accretion flow in  
these systems should be young. Moreover, a key element of disk warping and tearing due to Lense-  
Thirring precession is that mass needs to flow in from large inclination with respect to the black  
560 hole spin. Both conditions are satisfied if the accretion flow is formed, for instance, by a fully-  
stripped TDE. However, in this case the warped inner flow would be damped quite fast<sup>86</sup>, which  
would be in contrast with QPEs lasting at least months<sup>1</sup> (Figure 1 and 2) or even years<sup>2</sup>. A more  
quantitative comparison is beyond the reach of this work and of current disk warping and tearing  
simulations, but this is a promising scenario worth exploring in the future.

### **On the presence of an orbiting body**

565 Periodic variability is also often associated to binary systems of compact objects<sup>23</sup> and the  
connection with the quasi-periodic nuclear emission observed in QPEs is tempting. We here assume  
the main body to be a super-massive black hole ranging between  $\sim 10^4-10^7 M_{\odot}$  and we first consider  
the presence of a second orbiting super-massive black hole with a similar mass. There are several  
reasons which, when combined, disfavor such a scenario. Firstly, simulations show that the  
570 accretion flow of such objects is composed by a circum-binary disk with two inner small mini-  
disks<sup>87-89</sup>, which are thought to produce a quasi-sinusoidal modulated emission<sup>90,91</sup>. This signature  
can be detected in transient surveys<sup>92,93</sup> or in single sources<sup>94</sup>, with a well-known extreme case being  
OJ 287<sup>95,96</sup>. However, so far there is no evidence of such variability in optical and UV data<sup>1</sup> of QPEs  
(Fig. 1c and 2c), in particular in eRO-QPE1, which was covered in g- and r-band by the Zwicky  
575 Transient Facility DR3<sup>97</sup> until the end of 2019. Nor can this prediction be reconciled with the  
dramatic non-sinusoidal eruptions observed in X-rays, even in the case of binary self lensing<sup>98</sup>  
which can produce sharper bursts, albeit achromatic therefore in contrast with the energy

dependence of QPEs<sup>1,2</sup>. Moreover, we do not observe peculiar single- or double-peaked emission lines<sup>99-101</sup> and this can not be reconciled by enhanced obscuration<sup>102</sup>, since infrared photometry in QPEs is not AGN-like (WISE observed W1~W2 for the past 6-7 years) and X-rays do not indicate the presence of strong absorption. Secondly, super-massive black hole binaries are expected to form mostly via galactic mergers<sup>103,104</sup>, but the host galaxies of the two newly discovered QPEs look unperturbed (Extended Data Fig. 1a and 2a). Perhaps most importantly, a binary of super-massive black holes observed with a periodicity of the order of hours, such as the four observed QPEs, would show a large period derivative, due to gravitational wave emission, and would be relatively close to merger. To have (at least) four such objects very close to merger within  $z\sim 0.02-0.05$  is very unlikely<sup>105</sup> and would imply that they are much more common in the local Universe than observations suggest<sup>92,93</sup>.

Under the simplified assumption that the orbital evolution is dominated by gravitational waves emission, Extended Data Fig. 7 shows the allowed parameter space in terms of  $\dot{P}$  and  $M_2$  for a range of  $M_{\text{BH},1}\sim 10^4-10^7 M_\odot$  and zero or high orbit eccentricity ( $e\sim 0.9$ ), given the rest-frame period of both eRO-QPE1 and eRO-QPE2. We have additionally imposed  $M_2\leq M_{\text{BH},1}$ . For both sources we can draw a tentative line at the minimum period derivative that, if present, we would have measured already within the available observations: quite conservatively, we adopt a period decrease of one cycle over the 15 observed by NICER for eRO-QPE1 and the 9 observed by XMM-Newton for eRO-QPE2 (Fig 1d and 2c). Our constraint on  $\dot{P}$  is not very stringent for eRO-QPE1 and only high  $M_2$  and eccentricities are disfavored; instead, for eRO-QPE2 only an orbiting IMBH, or smaller, is allowed for zero eccentricity, while only a stellar-mass compact object is allowed for high eccentricity ( $e\sim 0.9$ ). Future observations of eRO-QPE1 and eRO-QPE2 in the next months may lead to tighter constraints on the mass and eccentricity of the putative orbiting body.

The preliminary conclusion of our analysis is that, if QPEs are driven by the presence of an orbiting body around a central black hole, it is more likely that this is a compact object with a mass significantly smaller than the  $\sim 10^4-10^7 M_\odot$  assumed for the main body. This scenario could make QPEs a viable candidate for the electromagnetic counterparts of the so-called extreme mass ratio inspirals (EMRI<sup>11-13</sup>), with considerable implications for multi-messenger astrophysics and cosmology<sup>14,15</sup>. Interestingly, it has been recently suggested for GSN 069 that a stellar-mass compact object orbiting around a super-massive black hole could be the origin of QPEs: a white dwarf of  $\sim 0.2M_\odot$  on a highly eccentric orbit ( $e\sim 0.94$ ) could reproduce the mass inflow rate needed to produce the observed X-ray luminosity averaged over a QPE cycle<sup>10</sup>. This is reminiscent of a suggested, albeit still observationally elusive, EMRI formation channel<sup>13,24-26</sup>. For GSN 069, a possible explanation of the QPE-free X-ray bright and decaying phase could be given by an accretion flow expanding and intercepting the body at a later time<sup>1</sup>; or if the orbiting body was originally a massive star and the stripped envelope produced the TDE-like behavior of the past decade<sup>1</sup> while the remaining core started interacting with the newly born or expanded accretion flow only at a later stage, which would also explain the relatively small mass required by the white dwarf calculations<sup>10</sup>. For the other QPEs which did not show evidence of a past X-ray bright and decaying phase, this scenario is not necessary and the interaction with a second stellar-mass (or more massive) compact object could qualitatively reproduce the periodic behavior (Extended Data Fig. 7b). Future X-ray observations of the known QPEs would help in further constraining the possible orbital evolution. It should be pointed out that these calculations so far only matched the average observed QPE luminosity with the mass inflow rate required to produce it<sup>10</sup>, but details on the exact physical mechanism that would produce these X-ray bursts are still elusive (see ‘On accretion flow instabilities’).

Finally, we address the lack of UV and optical variability in the scenario of an orbiting body. The X-ray plateau at minimum shows an almost featureless accretion disk thermal spectrum<sup>1-2</sup> (Extended Data Fig. 5), which could have been built up during the first orbiting cycles. This accretion flow

should be unusually small due to the lack of a broad line region<sup>3-4</sup> (Extended Data Fig. 1b and 2b), which would respond in light-days and that, if present, should have been observed in the SALT spectra taken months after the X-ray QPEs. The lack of strong UV and optical variability might be then due to the fact that the accretion disk is not large enough to even emit strong enough UV-optical radiation to emerge above the galaxy emission, which we can assume to be most of the observed  $L \sim 4.0 \times 10^{41} \text{ erg s}^{-1}$  ( $L \sim 4.3 \times 10^{41} \text{ erg s}^{-1}$ ) in the OM-UVW1 filter at 2910Å for eRO-QPE1 (eRO-QPE2). Using a simplified but physically motivated accretion disk model<sup>106</sup> for a spin zero black hole accreting at  $\sim 0.1$  Eddington, we computed the distance at which the bulk of 2910Å radiation would be emitted, namely  $\sim 1100$  and  $\sim 500 r_g$  for a mass of  $10^5$  and  $10^6 M_\odot$ , respectively. This would shift to even larger radii for increasing accretion rate (e.g.  $\sim 1850$  and  $\sim 860 r_g$  at  $\sim 0.5$  Eddington), while even for high spinning sources (spin  $\sim 0.9$ ) the peak of OM-UVW1 flux would still come from  $\sim 775$  and  $\sim 360 r_g$ . Furthermore, the predicted OM-UVW1 disk luminosity would be at least one or two orders of magnitude lower than the observed  $L \sim 4.0 \times 10^{41} \text{ erg s}^{-1}$  in the most luminous scenario. Therefore, even an UV-optical eruption 100 times brighter than the plateau would be barely detectable above the galaxy component.

*Predicted numbers.* Detailed self-consistency calculations on the predicted rate of such EMRI events, as compared to QPE rates, are required but are beyond the scope of this paper. Instead, we can provide here a rough model-independent estimate of the expected number of *observed* QPEs, regardless of their origin. Convolution of the black hole mass function<sup>107</sup> between  $\sim 10^{4.5}$ - $10^{6.5} M_\odot$  up to  $z \sim 0.03$  with the eROSITA sensitivity yields  $N \approx 100$ , which is then reduced with some educated guesses on a number of unknowns: during what fraction of their X-ray bright phase such sources undergo QPE behavior (the biggest unknown; e.g.  $>20\%$  for GSN 069); how many such sources are obscured and missed ( $\approx 2/3$ ); how many times we detect ongoing QPEs given the eROSITA sampling (depends on the period and the burst duration; e.g.  $\approx 20\%$  for GSN 069). This results in a (extremely uncertain) number of order unity per eRASS scan in the eROSITA-DE hemisphere, which is however in agreement with our pilot study of the first few months of eROSITA operations. Thus, the low observed numbers do not necessarily imply that these events are a rare phenomenon intrinsically and they can actually be a fairly common product of the black holes co-evolution with their host galaxies<sup>28</sup>. With a statistically meaningful sample of QPEs, inverting this calculation may allow us to constrain the black hole mass function in a poorly known mass regime<sup>27</sup>.

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#### **Author contributions.**

R.A. wrote the article, developed the method to search for QPE candidates, was PI of XMM-  
Newton and NICER follow-up observations, and performed most of the data analysis. A.Me. is PS/  
PI of eROSITA and followed and improved the project, the strategy of XMM-Newton and NICER  
855 follow-up observing campaigns and the writing of the article. K.N. followed and improved the  
project, the strategy of XMM-Newton and NICER follow-up proposals and the writing of the  
article. J.B. developed part of the code used for spectral and timing analysis and helped R.A. with  
XMM-Newton data analysis and with the development of the method to search for QPE candidates.  
M.Sa. led the counterpart association and significantly contributed to the interpretation and analysis  
860 of the photometry and optical spectroscopy. D.P. and R.R. performed most of the NICER data  
analysis. J.C. performed some of the analysis of optical spectroscopy and improved its  
interpretation. G.L. performed the astrometry of eROSITA and XMM-Newton data. G.P.  
significantly improved the writing of the article and encouraged the pursue of this project. A.Ma.  
And J.W. directly contributed to the analysis of XMM-Newton light curves, optical images and  
865 counterpart association. Z.A., K.G. and C.M. scheduled, monitored and processed NICER  
observations. D.A.H.B was PI of SALT observations and M.G. processed related data. E.K. and  
M.K. improved the scientific interpretation and presentation of the manuscript. M.E.R-C.  
contributed to the developing of the method to search for QPE candidates. A.R. contributed to  
XMM-Newton observing proposals and with A.S. led the triggering of SALT observations from the  
870 eROSITA-DE Consortium. M.Sc. performed and processed photometry data from the Rapid  
Response Robotic Telescope. All authors contributed to improve the projects from different sides  
throughout the process.

#### **Data and code availability**

875 With the exception of eROSITA proprietary data, data used in this work are public and available from the corresponding data archives or they will be soon, after the remaining proprietary period expires. Most of data may be available from the corresponding author on reasonable request.

### Competing interests

The authors declare no competing interests.

### Additional information

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**Extended Data Fig. 1 – eRO-QPE1 position and identification.** **a**, Legacy DR8 image cut-out around the optical counterpart of eRO-QPE1. Red and green circles represent the astrometry-corrected eROSITA and XMM-PN positions, respectively, with  $1\sigma$  positional uncertainties. The EPIC-PN position was corrected excluding the target (blue cross) to ensure an unbiased estimate of the possible positional offset. **b**, SALT spectra of eRO-QPE1 shown in black and blue with related  $1\sigma$  errors as shaded regions. The cyan spectrum represents a re-normalized sky spectrum to guide the eye for the residual sky feature around  $5577\text{\AA}$ .  
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**Extended Data Fig. 2 – eRO-QPE2 position and identification.** Same as in Extended Data Fig. 1, but for eRO-QPE2.  
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**Extended Data Fig. 3 – eRO-QPE1 spectral fit results.** XMM-Newton PN light-curve (top panel) and time-resolved spectroscopy fit results for spectra extracted in the 500 s time bins (bottom panels) of the two XMM-Newton observations of eRO-QPE1 using an accretion disk model (diskbb): in particular, the evolution of the peak accretion disk temperature and the normalization, which is proportional to the inner radius once distance and inclination are known. The quiescence level is fit combining the first part of both XMM-Newton observations. It is shown with a dashed line because due to low counts the fit is more uncertain (see Extended Data Fig. 5a). Median fit values and fluxes of the high and low eROSITA states are reported with orange and red arrows pointing left (upper limits are denoted with diagonal arrows).  $1\sigma$  uncertainties on the fit results are shown with shaded regions around the median.  
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**Extended Data Fig. 4 – eRO-QPE2 spectral fit results.** Same as Extended Data Fig. 3, but for eRO-QPE2.

**Extended Data Fig. 5 – eRO-QPE1 and eRO-QPE2 spectra.** **a**, XMM-Newton EPIC-PN source plus background spectra for eRO-QPE1. Red, orange and green data correspond to quiescence and to the peak of the second and first XMM-Newton observation, respectively, with error bars showing  $1\sigma$  uncertainties. The related solid lines show the unabsorbed source model obtained with diskbb, just for visualization. The grey line represents the background spectrum alone. The plateau is shown with a dotted line because due to low counts the fit is more uncertain. **b**, same as **a** but for eRO-QPE2. Here green data represent one of the peaks and the additional dashed lines indicate the absorbed source model.  
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**Extended Data Fig. 6 – The properties of QPEs’ host galaxies.** Stellar mass  $M_*$  and star formation rate (SFR) for eRO-QPE1 (blue) and eRO-QPE2 (red), with related  $1\sigma$  uncertainties; for eRO-QPE1 SFR is largely unconstrained (see Methods, ‘The host galaxies of QPEs’). For a comparison, normal galaxies<sup>66</sup>, TDEs<sup>57</sup> and CLAGN<sup>65</sup>, all below  $z < 0.1$ , are also shown.

915 **Extended Data Fig. 7 – Constraints on a secondary orbiting body. a,** Allowed parameter space in terms of period derivative and secondary mass  $M_2$  for a range of primary mass  $M_{\text{BH},1} \sim 10^4 - 10^7 M_\odot$  and zero (solid lines) or high orbit eccentricity ( $e_0 \sim 0.9$ , dotted lines), in which can reproduce the rest-frame period of eRO-QPE1. We have additionally imposed  $M_2 \leq M_{\text{BH},1}$ . We have drawn an approximate threshold at the minimum period derivative that, if present, we would have measured already within the available observations, corresponding to a period decrease of one QPE cycle over the 15 observed by NICER (Fig. 1d). The excluded region is shaded in red. **b,** same as **a** but for eRO-QPE2 and adopting as tentative minimum  $\dot{P}$  a period decrease of one cycle over the 9  
920 observed with XMM-Newton (Fig. 2c).

## Extended Data Table 1 - Summary of the observations performed

### 925 Extended Data Table 2 - Summary of spectral fit results for eRO-QPE1

The median value and related 16<sup>th</sup> and 84<sup>th</sup> percentile values are reported for every quantity; for unconstrained values  $1\sigma$  upper limits are quoted using the 84<sup>th</sup> percentile value of the parameter posterior distribution and are denoted with  $\downarrow$ . Reported results are obtained with the model `tbabs x diskbb`, with Galactic  $N_{\text{H}}$  frozen at  $2.23 \times 10^{20} \text{ cm}^{-2}$ , as reported by the HI4PI Collaboration<sup>48</sup>. Fluxes and luminosities are unabsorbed and rest-frame. The two eROSITA states are shown in Fig. 1a, whilst the three XMM-Newton observations in the table correspond to the three spectra in Extended Data Fig. 5a.  $F_{\text{disk}}$  is computed within 0.001 and 100 keV.

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### Extended Data Table 3 - Summary of spectral fit results for eRO-QPE2

Same as Extended Data Table 1, but for eRO-QPE2. Reported results are obtained with the model `tbabs x ztbabs x diskbb`, with Galactic  $N_{\text{H}}$  frozen at  $1.66 \times 10^{20} \text{ cm}^{-2}$ , as reported by the HI4PI Collaboration<sup>48</sup>; absorption in excess was estimated from ‘XMM quiescence’ and was allowed to vary within its 10<sup>th</sup> and 90<sup>th</sup> percentiles for all the other observations. The two eROSITA states are shown in Fig. 2a and model parameters in the low state are unconstrained; the two XMM-Newton observations in the table correspond to the spectra in Extended Data Fig. 5b.

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