The X-ray corona turns into the relativistic jet in the micro quasar GRS 1915+105

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GRS 1915+105¹ was the first stellar-mass black-hole in our Galaxy to display a superluminal

radio jet², similar to those observed in active galactic nuclei with a supermassive black hole

at the centre³. It has been proposed that the radio emission in GRS 1915+105 is fed by insta-

bilities in the accretion disc4 by which the inner parts of the accretion flow is ejected in the

jet^{5–7}. Here we show that there is a significant correlation between: (i) the radio flux, coming

from the jet, and the flux of the iron emission line, coming from the disc and, (ii) the tem-

perature of the corona that produces the high-energy part of the X-ray spectrum via inverse

Compton scattering and the amplitude of a high-frequency variability component coming

from the innermost part of the accretion flow. At the same time, the radio flux and the flux of

the iron line are strongly anti-correlated with the temperature of the X-ray corona and the

amplitude of the high-frequency variability component. These correlations persist over ~ 10 years, despite the highly variable X-ray and radio properties of the source in that period^{8,9}.

Our findings provide, for the first time, incontrovertible evidence that the energy that powers
this black-hole system can be directed either to the X-ray corona or the jet. When this energy
is used to power the corona, raising its temperature, there is less energy left to fuel the jet
and the radio flux drops, and vice versa. These facts, plus the modelling of the variability in
this source show conclusively that in GRS 1915+105 the X-ray corona morphs into the jet.

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The X-ray spectrum of black-hole binaries can be decomposed into three main radiation components: (i) A thermal component that dominates the emission at low (soft) energies 10 , below ~ 5 keV, due to an accretion disc through which mass flows from the binary companion to the black hole. (ii) A power-law like component that dominates the spectrum at energies above $\sim 5-10$ keV, caused by inverse-Compton scattering of the disc photons in a corona of highly-energetic electrons 11 . If the energy distribution of the electrons is Maxwellian, this component features a high-energy cut off at an energy that depends upon the electron temperature of the corona, kT_e . (iii) A broad emission line at $\sim 6.5-7$ keV due to iron, produced when photons from the corona reflect off the disc, with the line profile being set by special- and general-relativistic effects 12,13 . The X-ray emission of accreting black-hole binaries exhibits high-amplitude variability from tens of milliseconds to decades 8,14 . Depending on the relative importance of these spectral components and the strength of the variability, accreting black holes display different states 15 : In the hard states the X-ray spectrum ($\sim 1-20$ keV range) is dominated by emission from the corona, and the Fourier

power spectrum shows variability of up to 50% of the average luminosity over a broad range of time scales plus narrow quasi-periodic oscillations, QPOs. In the soft states the emission is dominated by the accretion disc, and the variability drops to less than 5% of the average luminosity.

Black-hole binaries in the hard states emit in radio with a spectrum that is consistent with self-absorbed synchrotron radiation from an optically thick and compact jet¹⁶. During the transition from the hard to the soft states, some black-hole binaries show radio emission from individual, spatially-resolved, plasma clouds that are ejected in a jet at speeds close to the speed of light. The radio spectrum of these discrete ejections is consistent with synchrotron emission from optically-thin material².

GRS 1915+105 harbours a $12^{+2.0}_{-1.8}$ solar-mass black hole¹⁷ and is very variable both in X-rays and radio wavelengths^{8,9}. In X-rays, the emission switches from times in which a bright accretion disc with a temperature $kT_{\rm bb}\approx 2$ keV and small inner-radius dominates the spectrum, to times in which the corona dominates the spectrum, the disc is relatively cool, $kT_{\rm bb}\approx 0.5-1$ keV and is inferred to have a large inner radius⁴. In several observations, mostly those with a cool disc, in addition to a band-limited noise component, a narrow and strong QPO, called type-C QPO¹⁸, appears in the Fourier power spectrum at frequencies between ~ 0.4 Hz and 6.5 Hz¹⁹. The frequency of the QPO increases as the temperature of the disc increases and the spectrum of the source softens. Besides this QPO (and harmonics and sub-harmonics of the fundamental frequency), the power spectrum of GRS 1915+105 sometimes shows a broad variability component at $\sim 60-80$ Hz²⁰ that we will call the high-frequency bump. The high-frequency bump appears when the spectrum of the

source is dominated by the corona, but observations in which the corona dominates the emission do not always show this high-frequency bump. At the same time, observations of GRS 1915+105 in which the spectrum is dominated by the corona are sometimes, but not always, accompanied by high radio fluxes^{21,22}. (We show the power-density spectra of two observations of GRS 1915+105 with the QPOs and the bump indicated in the Extended Data Figure 5.)

We studied a large dataset of 1800+ X-ray observations of GRS 1915+105 obtained with 57 the Rossi X-ray Timing Explorer (RXTE) between 1996 and 2012, combined with almost daily 58 observations of the source at 15 GHz with the Ryle telescope. Our final sample consists of 410 59 observations for which we have simultaneous data both in X-rays and radio. For each of these ob-60 servations we have a measurement of (i) the radio flux density at 15 GHz, (ii) the X-ray hardness 61 ratio calculated as the ratio of the intensity in the 13-60 keV to the 2-7 keV band, (iii) the frequency of the fundamental component of the type-C QPO, (iv) the phase lag at the QPO frequency 63 for photons in the 5.7-15 keV band with respect to those in the 2-5.7 keV band, (v) the 2-60keV fractional rms amplitude of the high-frequency bump, and (vi) the best-fitting parameters to the X-ray energy spectra of the source. (See the section Methods for details of the analysis and an explanation of some of these quantities). These vastly different types of data, consisting of X-ray and radio fluxes and spectral and timing properties of a single source, come from wavelengths that are more than eight orders of magnitude apart and sample time scales that are more than eleven orders of magnitude different, from ten milliseconds to a decade.

In Figure 1 we plot the X-ray hardness ratio as a function of the frequency of the QPO for

these 410 observations of GRS 1915+105. The x and y axes of the four panels in this Figure are the same, while the colours of the points in each panel represent, respectively, the simultaneous 15-GHz radio-flux measurements from the jet (Fig. 1a), the electron temperature of the X-ray corona (Fig. 1b), the flux of the iron emission line in the X-ray spectrum (Fig. 1c), and the fractional rms amplitude of the high-frequency bump (Fig. 1d). In all four panels blue (red) indicates high (low) values of the quantity represented by the colours.

The QPO frequency generally increases as the hardness ratio decreases and the source spectrum softens, consistent with a decreasing inner radius of the accretion disc that leads to an increase of both the disc flux¹⁰ and QPO frequency^{23,24}. The relation, however, is significantly broader than the spread expected from the errors in each quantity. (The errors are smaller than the size of the points.)

The colours of the points in the four panels of this Figure show that the radio flux, the flux of the iron line, the temperature of the corona and the fractional rms amplitude of the high-frequency bump depend upon both QPO frequency and hardness ratio. This double dependence is the reason for the striking match between the two panels on the left and the two on the right, and the almost perfect mirror match between the two top and the two bottom panels. In other words, the breadth of the hardness-ratio/QPO-frequency relation is consistently set by either of the four quantities, such that if we plotted the data in a diagram with the QPO frequency along the x axis, the hardness ratio along the y axis and any of these four quantities along the z axis, the points would lie on a 2-dimensional surface in 3D.

The two panels of Figure 2 show the flux of the iron line as a function of the X-ray flux in the 2–25-keV band for all observations of GRS 1915+105. In the left panel the colour of the points represents the temperature of the corona, while in the right panel the colours represent the phase lags between the 2–5.7 keV and 5.7–15 keV bands at the frequency of the QPO. While the flux of the iron line increases as the total flux of the source increases, when the temperature of the corona is low, the radio flux is high and the lags at the QPO frequency are positive the correlation is steeper than when the temperature is high, the radio flux is low and the lags are negative. To confirm that our measurements of the line flux are not biased because of the relatively low spectral resolution of the RXTE/PCA instrument, we also include in this Figure independent measurements of the flux of the line with Chandra and Suzaku taken from the literature 25,26 (black plus and cross symbols).

These results provide a unique clue to understand the nature of the corona and the jet in this object, and what powers these components. Inverse Compton scattering cools down the corona by transferring energy from the electrons to the soft disc photons. The temperature of the corona in black-hole binaries, however, increases during periods in which the photon flux of the disc drops and Compton cooling is less effective. This means that a source of power balances the inverse Compton cooling and sets the temperature of the corona. Our findings show that in GRS 1915+105 the energy provided by this mechanism is split to either power the jet or heat the corona.

The thermal energy stored in a spherical corona of optical depth τ and size L around a black hole of mass M is $E_{th} \approx 3.4 \times 10^{26} \tau \left(\frac{kT_e}{1~{\rm keV}}\right) \left(\frac{M}{M_\odot}\right)^2 \left(\frac{L}{R_g}\right)^2$ erg, where $R_g = GM/c^2$ is the

gravitational radius of the black hole and G and c are, respectively, the gravitational constant and the speed of light²⁷.

As discussed in the section Extended Results and Discussion, the change of sign of the lags 114 is explained if a fraction of the disc photons that are Comptonised in the corona impinges back 115 onto the disc before reaching the observer²⁸. When this feedback fraction is low, time delays due 116 to Comptonisation dominate and the lags are positive; when this fraction is high, reprocessed disc 117 photons reach the observer later than those from the corona and the lags become negative. Taking 118 the corona sizes from fits with this model²⁹, $L\approx 10-1200R_a$, plus $\tau\approx 1-6$ and $kT_e\approx 5-40$ keV 119 from the spectral fits, we find that $E_{th} \approx 10^{31} - 10^{35}$ erg. If this energy is released over the time 120 scale of the high-frequency bump¹, the thermal luminosity is 2 to 5 orders of magnitude lower 121 than the observed luminosity of the corona in GRS 1915+105. The alternative is that the corona 122 is powered by magnetic energy^{27,30}, e.g., shear energy due to differential rotation of the magnetic-123 field lines that thread the accretion disc. This magnetic energy would also be responsible for the synchrotron radio emission and the jet ejection mechanism in black-hole binaries. 125

We propose that in GRS 1915+105 the corona turns into the jet and that both are, at different times, the same physical component. Based on the results shown here and fits with the model of the lags that we present in the section Extended Results and Discussion, the process proceeds as follows: (1) When the QPO frequency is ~6 Hz the corona is relatively large and enshrouds the inner parts of the accretion disc (Fig. 3a); as seen from the corona, the disc covers half of the sky Note that this is the shortest variability time scale in the data; using any other time scale longer than this one to estimate the thermal luminosity would make the discrepancy even bigger.

and hence there is a high probability that photons from the corona return to the disc leading to a high feedback fraction and negative QPO lags. As the QPO frequency decreases from \sim 6 Hz to \sim 2 Hz, the inner edge of the disc moves outwards and the magnitude of the lags and the size of 133 the corona decrease. In this phase the magnetic field that threads the disc and powers the corona 134 is relatively disorganised, the magnetic energy is dissipated stochastically leading to a high corona 135 temperature. (2) At a QPO frequency² of \sim 2 Hz the size of the corona becomes equal to the 136 truncation radius of the accretion disc, the feedback fraction decreases abruptly and the QPO lags 137 become zero. From this point on the corona moves inside the accretion disc (Fig. 3b), the magnetic 138 field starts to become coherent on longer spatial scales, the stochastic energy dissipation decreases 139 and the temperature of the corona drops. At the same time the magnetic-field lines start to channel 140 material from the corona into the direction perpendicular to the accretion disc, and low-level radio 141 emission from the jet starts to appear. (3) As the QPO frequency continues decreasing below ~ 2 142 Hz the inner disc radius moves further out and the size of the corona increases again but, given 143 that the lags are positive, this time the feedback fraction remains low. From this it follows that 144 the corona does not cover the inner parts of the disc, which can only be the case if the geometry 145 of the corona changes such that it becomes more prominent in the direction perpendicular to the 146 disc (Fig. 3c); as seen from the corona, the disc now covers a much smaller area of the sky. As the 147 magnetic-field lines become more spatially coherent³¹ there is less stochastic energy dissipation, 148 the corona temperature drops further and the material from the corona that was channeled off the originally extended corona is expelled away from the accretion-disc plane and becomes the radio ²The transition occurs when the lags fo the QPO change from negative to positive; although the exact value of the QPO frequency¹⁹ at which this transition occurs is between 1.8 and 2 Hz, here we will always write 2 Hz for simplicity.

151 jet (Fig. 3d).

Our multi-wavelength correlations match the proposal that, during the initial parts of an outburst, the X-ray corona of the black-hole binary MAXI J1820+070 contracts³² and then reexpands³³. Here we show conclusively that, as previously speculated^{7,34,35}, in the case of GRS
1915+105 the contracting corona becomes the radio jet and that, at least part of the time, the
corona and the jet are actually one and the same physical component^{36–38}.

The appearance of radio flares when the QPO frequency is below 2 Hz reinforces our interpretation. Figure 4 shows that in the periods that the frequency of the QPO moves more or less
stochastically between ~2 Hz and ~8 Hz (red circles) the radio flux (light blue curve) is low. Occasionally, the QPO frequency evolves in a more systematic way: it starts to decrease, crosses the
value of 2 Hz and moves up again; at the same time the radio flux increases sharply and a radio
flare lasting a few tens of days is observed. Figure 4 shows this behaviour over a period of about
500 days in which the source shows two radio flares. Extended Data Figure 9 shows that the same
behaviour repeats consistently over a period of 10 years and about a dozen radio flares.

The relation between the iron-line flux and the total flux is consistent with the above scenario.

The flux of the iron line depends more strongly upon X-ray flux when the temperature of the corona is low, that is when the corona has turned into the jet²⁵, than when the corona is more extended and covers the inner parts of the accretion disc (Fig. 2). This points to a lamp-post geometry³⁹ with the corona, which is now the jet, illuminating the disc anisotropically^{40,41}. Because the jet does not cover the accretion disc, the flux of the iron line is not (or mildly) attenuated by the corona^{42,43}.

The behaviour we observe in GRS 1915+105 could explain the deviations from a single track in the radio/X-ray correlation of other accreting galactic black holes^{44–49} If, as in the case of GRS 1915+105, the energy powering these systems is used to either accelerate the jet or heat the corona, different sources, or the same source at different times, will show lower radio fluxes at a given X-ray flux (or, equivalently, higher X-ray fluxes at a given radio flux), depending on how much energy is directed towards, respectively, launching the radio jet or heating the X-ray corona.

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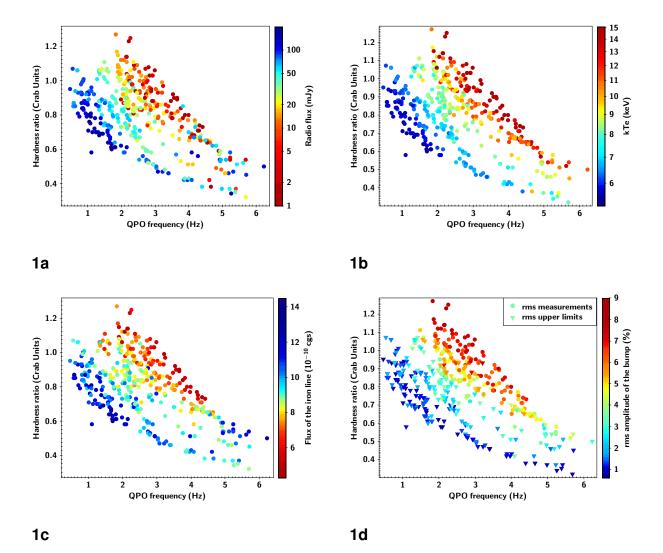
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Author Contributions All authors contributed to interpretation of results and edited the manuscript. M.M. led the interpretation, obtained spectral parameters and wrote the manuscript. K.K. wrote the model that triggered this research, produced initial radio/timing plots, fitted rms and lag spectra and co-led the interpretation. F.G. produced initial 3D radio/timing/spectral plots, fitted rms and lag spectra of the QPO and co-led the interpretation. M.M., K.K. and F.G. measured extra QPO frequencies. L.Z. obtained parameters of the QPO. Y.Z. obtained parameters of the high-frequency bump. T.M.B. had the idea to study the high-frequency bump in connection with the radio flux. D.A. and O.B. discussed the results and contributed to the interpretation.

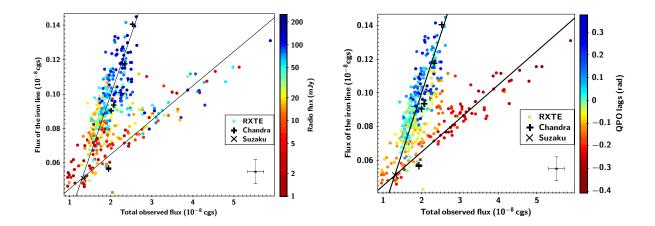
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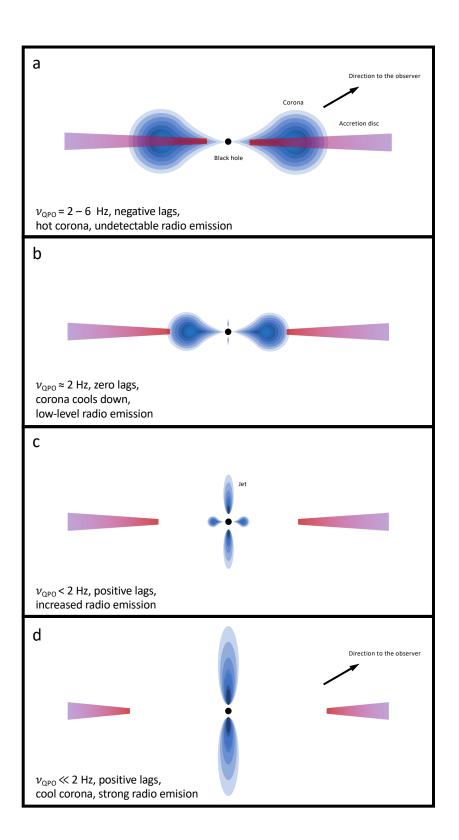
1 Hardness ratio vs. QPO frequency of GRS 1915+105

Each point corresponds to one of the 410 observations of GRS 1915+105. The hardness ratio is the ratio of the observed intensity from 13-60 keV to 2-7 keV in units of the Crab nebula. Average errors of the QPO frequency and hardness ratio are, respectively, ± 0.05 Hz and ± 0.001 Crab units, and are both smaller than the size of the points. The colour of the points in each panel represent: a, The 15-GHz radio-flux with average error of $\pm (1-5)$ mJy. b, The electron temperature of the X-ray corona with average error of ± 0.75 keV. c, The flux of the iron emission line with average error of $\pm 0.7 \times 10^{-10}$ erg cm⁻² s⁻¹. d, The fractional rms amplitude of the high-frequency bump with average error of $\pm 0.7\%$. In panel d the circles indicate measured values and the triangles upper limits. (All errors and upper limits in this work represent $1-\sigma$ and 95% confidence intervals, respectively.)



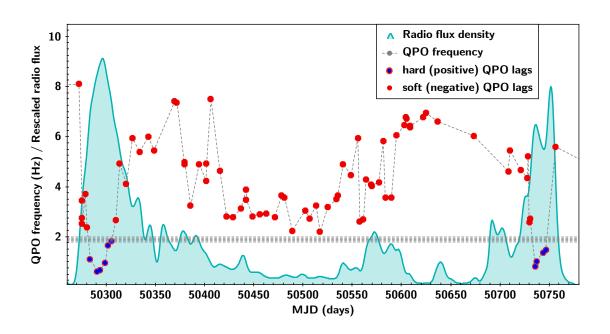
2 Flux of the iron line vs. total flux in the 2-25 keV range for GRS 1915+105

Each coloured point corresponds to one of the 410 observations of GRS 1915+105. The colour scale represents the temperature of the corona (left panel) and the phase lags of the QPO in radians (right panel). Negative (positive) lags indicate that, at the QPO frequency, the soft photons in the band 2-5.7 keV arrive after (before) the hard ones in the band 5.7-15 keV. The average error of the plotted quantities is shown at the bottom right of the plots. The lines indicate the two separate correlations. The plus and cross symbols correspond to measurements of the flux of the line using observations of, respectively, Chandra²⁵ and Suzaku²⁶.



3 Schematic picture of the corona turning into the jet in GRS 1915+105

When the QPO frequency is in the 2-6 Hz range the lags are negative, the corona is hot and extended, and covers the inner parts of the disc (panel a). The magnitude of the lags and the size of the corona decrease and the inner disc radius increases as the QPO frequency decreases. When the QPO frequency is \sim 2 Hz the lags are zero and the size of the corona is equal to the inner radius of the accretion disc (panel b). As the frequency of the QPO decreases further below \sim 2 Hz the lags turn positive and the corona becomes the jet (panels c and d).



4 Time evolution of QPO frequency and radio flux for GRS 1915+105

The points connected by a line show the time evolution of the frequency of the QPO in the X-ray power spectrum of GRS 1915+105. The light-blue curve (smoothed with a Gaussian kernel) shows the simultaneous measurements of the radio flux density at 15 GHz (y axis rescaled). A strong radio flare appears on the two occasions in which the lags of the QPO turn from soft (red points) to hard (red/blue points), corresponding to the QPO frequency crossing from above to below \sim 2 Hz. The horizontal band shows the range of QPO frequencies over which the transition occurs. Here we show the first two radio flares in our data, but the same behaviour occurs consistently for all radio flares during our observations (see Supplementary Material).

177 Methods

Power spectra: We examined all the RXTE archival observations of GRS1915+105 from 1996 to 2012 obtained with the Proportional Counter Array (PCA). The observations that we used for our analysis belong to the class⁸ χ , state C, equivalent to one of the hard states in other (transient) black-180 hole sources. For each observation we computed the Fourier power spectrum in the full energy band (absolute PCA channel 0-249) every 128 s with a time resolution of 1/512 s, corresponding 182 to a Nyquist frequency of 256 Hz. We averaged all the 128-s power spectra within an observation, subtracted the contribution due to Poisson noise⁵⁰ and normalised⁵¹ these averaged power spectra to 184 units of fractional rms squared per Hz. (We ignored the background count rate for this calculation 185 since it was always negligible compared to the source count rate.) We subsequently applied a 186 logarithmic frequency rebin to the data such that the size of a bin increases by $\exp(1/100)$ with 187 respect to the size of the previous one, and we used XSPEC version 12.9 to fit the resulting power 188 spectra with a sum of Lorentzian functions⁵² that represent the broad-band noise component and 189 a number of QPOs¹⁹. As in previous studies²⁰ we included a Gaussian component centred at zero 190 frequency in the model to fit a high-frequency bump at 60-80 Hz in the power spectra. (We show 191 two power spectra with the best-fitting model in Extended Data Figure 5.) For the rest of the 192 analysis we selected only observations where at least one narrow QPO peak is present on top of the broad-band noise component in the power spectra, which is typical for the type-C QPOs¹⁸. Based on the fitting results we only retained features that were detected at a significance greater than $3-\sigma$ and had a Q factor, defined as the ratio of the QPO frequency to its width, of 2 or more. We further checked the spectrogram of each observation, which shows visually the Fourier power

spectrum as it varies with time, and excluded ~ 130 observations in which the QPO frequency changed significantly within a full RXTE observation. Our final sample contains a total of 620 observations.

Lag spectra: Following the method described in^{53,54} we produced a frequency-dependent phase-201 lag spectrum (lag-frequency spectrum) between the 2-5.7 and 5.7-15 keV energy bands for each 202 observation. Since our sample includes observations during the PCA calibration epochs 3-5, 203 to account for changes in the PCA channel-to-energy gain factor we selected the closest absolute 204 channels that matched these energy bands, but the exact boundaries of each band still differ slightly 205 between epochs. To calculate the phase lags of the QPO we averaged the lag-frequency spectra around the centroid frequency of the QPO, $\nu_0 \pm FWHM/2$, where FWHM is the full-width at 207 half-maximum of the Lorentzian that we used to fit the QPO profile. In principle, the phase lags 208 in the range of frequencies of the QPO can be affected by the lags of the underlying broad-band noise component. However, in GRS 1915+105 the rms amplitude of the QPO is much higher than 210 that of the broad-band noise and the phase lags at the frequency of the QPO are dominated by 211 the QPO itself, with the contribution of the noise component being negligible⁵⁵. In this work, a 212 positive (negative) lag means that the hard photons lag (lead) the soft photons. No correction for 213 the dead-time-driven cross-talk⁵⁶ was done because this effect was found to be negligible. (See¹⁹ 214 for other details of the timing analysis.) In Extended Data Figure 6 we show nine representative 215 power and lag-frequency spectra covering the range of frequencies of the QPO in GRS 1915+105.

Energy Spectra: We used the RXTE/PCA³ Standard 2 data to extract energy spectra separately for each observation in our sample. We corrected the energy spectra for dead time and used the FTOOLS PCABACKEST and PCARSP in HEADAS v.6.27 to, respectively, extract background spec-219 tra and produce response files for each observation. We fitted the energy spectra of all observa-220 tions jointly with the model VPHABS*(DISKBB+GAUSS+NTHCOMP). The component VPHABS 221 accounts for the interstellar absorption along the line of sight to the source; we used the abundance 222 and cross-section tables given by 57 and 58 , respectively, with the column density of hydrogen, $N_{\rm H}$, 223 linked across observations and free to vary. Because $N_{\rm H}$ in the direction of GRS 1915+105 is quite 224 high⁵⁹, $N_{\rm H} \gtrsim 6 \times 10^{22}$ atoms cm⁻², we also let the abundance of iron in the interstellar material free 225 to vary, since neutral iron produces an absorption edge at $E{\approx}7.1$ keV that was apparent in the fit 226 residuals. The component DISKBB⁶⁰ represents the emission from an optically thick and geometri-227 cally thin accretion disc, and has parameters $kT_{\rm bb}$ and $N_{\rm dbb}$ that are, respectively, the temperature 228 at the inner disc radius and the normalisation of the component defined as the ratio of the inner 229 disc radius to the distance to the source squared multiplied by the cosine of the inclination of the 230 disc with respect to the line of sight. The component NTHCOMP⁶¹ represents the emission due to 231 inverse-Compton scattering from the corona. The parameters of this component are the power-law 232 index, Γ , the electron temperature of the corona, $kT_{\rm e}$, the temperature of the source of soft pho-233 tons that enter into, and are up scattered in, the corona, $kT_{\rm seed}$, and a normalisation that gives the flux density at 1 keV. We assumed that the source of seed soft photons is the accretion disc, and ³We also fitted the RXTE/HEXTE (High Energy X-ray Timing Experiment) data of those observations in which the instrument was operational; the results were consistent with the ones of the RXTE/PCA, but since data of this instrument were not available for all observations, we did not use the RXTE/HEXTE data for the rest of the analysis.

linked the temperature $kT_{\rm seed}$ to the temperature of the DISKBB component for each observation separately during the fits. In this model, the optical depth of the corona, τ , assumed to be ho-237 mogeneous, is a function Γ and kT_e . Finally, the component GAUSS represents a broad iron 238 emission line at 6.5-7 keV due to reflection of corona photons off the accretion disc^{12,13}. While a full reflection model^{62,63} would be more appropriate to describe this effect, the PCA instrument 240 does not have enough spectral resolution to distinguish between the profile of a line in a full reflection model and a Gaussian component. The parameters of the GAUSS component are the energy, 242 width and total photon flux of the line, $E_{\rm g}$, σ , and $N_{\rm g}$, respectively. Finally, we calculated the 243 total observed flux of the source and the intrinsic (i.e., not affected by interstellar absorption) flux 244 of the full model and of all the individual model components in the 2-25 keV energy range. In 245 Extended Data Figure 7 we show the energy spectra, with the best-fitting model, of the same two 246 observations in Extended Data Figure 5. 247

If the iron emission line is due to reflection of corona photons off the accretion disc, and 248 the width of the line is a consequence of Doppler boosting, Doppler beaming and gravitational redshift, it would be more appropriate to use a full reflection component that includes relativistic 250 broadening instead of a Gaussian to fit the spectrum. To explore this we fitted all the spectra 251 with the model VPHABS*(DISKBB+RELXILLCP+NTHCOMP), where the component REXILLCP⁶³ 252 represents the reflection off the accretion disc of the emission from the NTHCOMP component. 253 Compared to the fits with a Gaussian, this model has six extra free parameters. Given that the 254 RXTE/PCA instrument has limited spectral resolution and does not extend below ~ 3 keV, the 255 model is insensitive to some of the parameters of REXILLCP, and some of these parameters become

highly correlated with those of the DISC component. We therefore fixed the spin of the black hole to $a_* = 0.95$ (ref. [59]) and the inclination angle of the accretion disc to the line of sight to $i=65^{\circ}$ (ref. [2]). We further linked the two emissivity indices during the fits, which eliminates 259 the parameter that gives the radius in the disc at which the power-law index of the emissivity profile 260 changes, and fixed the inner radius of the disc at the radius of the innermost stable circular orbit⁵⁹. 261 Finally we linked the power-law index, Γ , and the electron temperature, kT_e , of RELXILLCP to 262 the corresponding parameters of NTHCOMP. The extra free parameters of the fit are one emissivity 263 index, the reflection fraction, the ionisation parameter and the iron abundance of the disc. We 264 obtain equally good fits as with the model above, with the reflection fraction ranging from 1% 265 to 20%. Because the reflected component is much-lower than the Comptonised component, the 266 parameters of the NTHCOMP in these fits are consistent with those from the fits with a Gaussian 267 line. The biggest impact of fitting the spectra with a reflection component is that the parameters of 268 the disc are less well constrained in the model with REXILLCP than in the model with a Gaussian. 269 This is understandable given that the emission of the reflection component at energies below $\sim 4-5$ 270 keV, where the disc emission peaks, is higher than that of a Gaussian.

The REXILLCP model does not provide the flux or the equivalent width of the Gaussian, however the reflection fraction of RELXILLCP is generally correlated with the parameters of the line⁶⁴.

We plotted the flux of the iron line from the fits with a Gaussian against the reflection fraction from
the fits with RELXILLCP and confirmed that this is indeed the case in our fits. We therefore obtain
similar plots to those in Figure 2 if instead of the flux of the Gaussian line we plot the reflection
fraction of RELXILLCP vs. total flux. We prefer to use the former because, as we explained above,

the model with a Gaussian line has less free parameters than the full reflection model which, given
the limited spectral resolution of the RXTE/PCA instrument, leads to degeneracies of the parameters in the fits with the full reflection model, and because by using a Gaussian we can easily include
in the plot the measurements of the flux of the iron line obtained with Chandra and Suzaku, as we
did in Figure 2.

Hardness ratio: For each RXTE observation of GRS 1915+105 we computed a hardness ratio value defined as the ratio of the background-subtracted count rate of the source in the 13–60 keV band to that in the 2–7 keV band. As with the lag-frequency spectra, we selected the closest absolute channels that matched these energy bands in each PCA gain epoch. Before calculating the ratios, we corrected each observed count rate for instrumental dead time and normalised them by the count rate in the same band from the Crab nebula to account for possible changes of the effective area of the instrument with time.

Radio fluxes: For the flux-density data of GRS 1915+105 in radio we used measurements⁹ from
the Ryle Telescope at 15 GHz with the four mobile antennas set in a compact array configuration
within 100 m of the nearest fixed antenna yielding a resolution of ~30 arcsec at that frequency.
The flux-density scale was calibrated with observations of the nearby quasars 3C 48 or 3C 286.
The observations consist mostly of 32-s samples with an rms noise of 6 mJy that decreases as the
square root of the integration time; flux-density values below about 1 mJy may be unreliable. See⁹
for other details of the analysis of the radio data.

Finally, we cross-correlated all the X-ray and radio data based on the date of the observations,

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which left us with a sample of 410 observations with simultaneous radio flux densities at 15 GHz and X-ray energy, power-density and lag-frequency spectra and hardness ratios.

Having described the observations and analysis we used, it is worth noting that the measurements presented in this paper come from very different types of data and totally independent analysis techniques: The hardness ratio, iron-line flux and $kT_{\rm e}$ come from X-ray light curves and time-averaged energy spectra, the frequency and lags of the QPO and the rms amplitude of the high-frequency bump come from Fourier power spectra of high-time resolution data, and the radio flux was measured independently in a totally different frequency band than the X-ray data.

306 Extended results and discussion

Fits to the power spectra: In Extended Data Figure 5 we plot two representative Fourier power 307 spectra of GRS 1915+105 to show both the type-C QPO and the high-frequency bump. The power 308 spectrum plotted in black corresponds to the observation from September 21 1998 (ObsID 30703-309 01-34-00), while the power spectrum plotted in blue corresponds to the observation from April 310 10 1998 (ObsID 30402-01-09-01). Both power spectra were calculated using photons from the 311 full PCA band, nominally 2-60 keV. The QPO is the narrow feature that appears in both power 312 spectra at ~ 2 Hz, with a second harmonic and subharmonic at, respectively, ~ 4 Hz and ~ 1 Hz. 313 In the case of GRS 1915+105 it is relatively straightforward to distinguish the QPO fundamental 314 from the subharmonic and harmonic components because the QPO fundamental, subharmonic and 315 harmonic components show very different rms amplitude and lags dependence when plotted vs. 316 their own frequency¹⁹, and the fundamental is always the strongest peak in the power spectrum. 317

The model includes also two broad Lorentzians centred, respectively, at 0 Hz and 2.5 Hz to 318 fit the the broad-band noise component in the power spectrum. The high-frequency bump is the 319 broad feature extending up to ~ 100 Hz in the black power spectrum^{52,65–70}. We fitted this bump 320 with a zero-centred Gaussian and let the width and normalisation free to vary during the fits. It 321 is apparent that the QPO at 2 Hz and its second harmonic and subharmonic are present in both 322 power spectra, but the high-frequency bump is only present in the observation of September 1998 323 and significantly absent in the one of April 1998. We computed the rms amplitude of the high-324 frequency bump by integrating the power of the best-fitting Gaussian from 0 Hz to ∞ . The rms 325 amplitude of the high-frequency bump in the observation of September 1998 is $8.0\pm0.3\%$ of the 326

total luminosity of the source in the 2-60 keV band, whereas the 95% confidence upper limit of the rms amplitude in the observation of April 1998 is only 1% of the total luminosity. Since the high-frequency bump was not significantly detected in the observation of April 1998, to calculate 329 the upper limit we fixed the width of the Gaussian to the value we obtained from the fit to the observation of September 1998. We followed the same procedure to compute the rms amplitude 331 or, when appropriate, the upper limits of the high-frequency bump in the rest of the observations. 332 In the observations in which the high-frequency bump is significantly detected the width of this 333 feature ranges from ~ 30 Hz to ~ 100 Hz. In those observations in which the high-frequency bump 334 was not significantly detected, to compute the upper limits we fixed the width of the Gaussian to 335 70 Hz, which is the average value that we obtained from the fits of the observations in which the 336 high-frequency bump was significantly detected. We report a detailed analysis of the properties of 337 the high-frequency bump in a separate paper⁷¹. 338

Fits to the energy spectra: In Extended Data Figure 7 we show the energy spectra of the same 339 two observations for which we show the power spectra in Extended Data Figure 5. The spectrum plotted in black corresponds to the observation from September 21 1998 (ObsID 30703-01-34-341 00), while the spectrum plotted in blue corresponds to the observation from April 10 1998 (ObsID 342 30402-01-09-01). This Figure shows that the flux of the source was lower and, at the same time, 343 the spectrum was harder (extending to higher energies) in September 1998 than in April 1998. 344 This difference is reflected in the values of the best-fitting temperature of the corona in these two 345 observations, which are $kT_{\rm e}=10.9\pm0.8$ keV and $kT_{\rm e}=6.3\pm0.5$ in the observations of September 346 1998 and April 1998, respectively. From the comparison of this Figure and Extended Data Figure 5 it is apparent that the high-frequency bump is present when the temperature of the corona is high.

Indeed, when we fit all the observations we find that the rms amplitude of the high-frequency bump

is higher when the temperature of the corona is higher, regardless of the values of the hardness ratio

and QPO frequency in each observation (see Figure 1).

Energy-dependent rms amplitude and phase lags of the QPO. The corona becomes the jet:

In Extended Data Figure 6 we plot the power- and lag-frequency spectra of nine observations of

GRS 1915+105, representative of the range of frequencies covered by the type-C QPO. The phase

lags of the QPO change from positive when the frequency of the QPO is lower than \sim 2 Hz to

negative when the frequency of the QPO is higher than \sim 2 Hz. (See¹⁹ for details of this result and a

discussion of the implication of this behaviour.) At the same time, as the QPO frequency increases

the slope of the lag spectrum decreases²⁹, going from positive when the frequency increases from

from \sim 0.5 Hz to \sim 2 Hz, to 0 when the frequency is \sim 2 Hz, and finally to negative when the QPO

frequency increases further from \sim 2 Hz to \sim 6 Hz.

The energy-dependent rms amplitude and phase lags of the QPO in GRS 1915+105 are well explained by a time-dependent model²⁸ in which photons from the accretion disc are inverse Compton scattered in a corona of characteristic size L, and a fraction of those photons subsequently impinges back onto the disc before reaching the observer. The time-averaged version of this variability model is equivalent to the NTHCOMP model in XSPEC. In the current version of the model we assume that the corona is spherically symmetric and has constant optical depth and electron temperature. Most likely the geometry of the corona is more complex than that, and the optical depth and electron temperature change as a function of the distance to the black hole. In a non-

spherical corona the rms amplitude and lags of the QPO may change with the inclination of the binary system with respect to the line of sight^{72,73}. We note, however, that both the rms amplitude and lags of the QPO in this and other sources change in a systematic way with QPO frequency, which in turn changes over time scales of minutes to hours, much faster than potential changes of the binary inclination that are expected to happen over periods of a few tens of days to a few thousand years⁷⁴. This evinces that, although inclination may play a role, the thermodynamical properties of the corona have a much larger effect than inclination in setting the rms amplitude and lags of the QPO.

Fits with this time-dependent model to the data of GRS 1915+105 show^{29,75} that, as the QPO 377 frequency decreases from \sim 6 Hz to \sim 2 Hz, the feedback fraction is close to 100% and remains more or less constant. At the same time the size⁴ of the corona decreases from $L \approx 1000-2000$ km 379 $(\sim 60-120~R_q$ for a 12 solar-mass black hole) to $L\approx 100~{\rm km}~(\sim 6-10~R_q)$, the lags are negative and their magnitude decreases. At a QPO frequency of \sim 2 Hz the corona size is minimum, the feedback 381 fraction drops abruptly to zero and the lags become zero. If the QPO frequency is produced by 382 Lense-Thirring precession^{23,24} of the inner edge of the accretion disc, at a QPO frequency of 2 Hz 383 the size of the corona is more or less equal to the inner disc radius (dashed line in Extended Data 384 Figure 8). When the QPO frequency decreases below \sim 2 Hz, the corona size increases again up 385 to $L\approx 2\times 10^4$ km ($\sim 1200~R_q$) at the lowest QPO frequency, the feedback fraction remains constant 386 close to zero and the lags become positive and increase with decreasing QPO frequency. Although ⁴In the model we solve the Kompaneets equation⁷⁶ for a spherical corona; since the actual geometry of the corona is likely different, the values given here should be considered as a characteristic size of the corona.

the size of the corona increases again when the QPO frequency is below \sim 2 Hz, the fact that the feedback fraction is close to zero whereas when the QPO frequency is above \sim 2 Hz the feedback fraction is high, implies that the corona does not cover the inner parts of the accretion disc. This in turn demonstrates that the geometry of the corona has changed (see Fig. 3).

Extended Data Figure 9 shows the time evolution of the QPO frequency superimposed on 10 392 years of the radio flux measurements of GRS 1915+105 with the Ryle telescope. To produce this 393 Figure we reanalysed all the RXTE observations in the period of the radio monitoring campaign, 394 and added 357 observations with QPOs that were not in the sample of 410 observations discussed 395 so far. These 357 observations were not included in the original analysis 19 because the QPO frequency drifts by a few tenths of Hz in the observation period, which could bias the measurement 397 of the rms and lags of the QPO. But since the frequency drift is only slightly larger than the error 398 of the average QPO frequency in each observation, we decided to use these data for this Figure 399 because this allows us to have a denser coverage of the time evolution of the QPO frequency during 400 the radio monitoring campaign. Extended Data Figure 9 shows that the intervals of strong radio 401 flares⁵ coincide with the times when the QPO frequency is below 2 Hz. This behaviour repeats 402 consistently for all the radio flares in these observations; there is no radio flare in which the QPO 403 frequency is not below 2 Hz, and there is no case of a QPO frequency below 2 Hz without a radio 404 flare. Given the data, we estimated that the probability of having a QPO frequency below 2 Hz and 405 a radio flare at the same time if the two phenomena were uncorrelated is less than 2×10^{-10} . 406

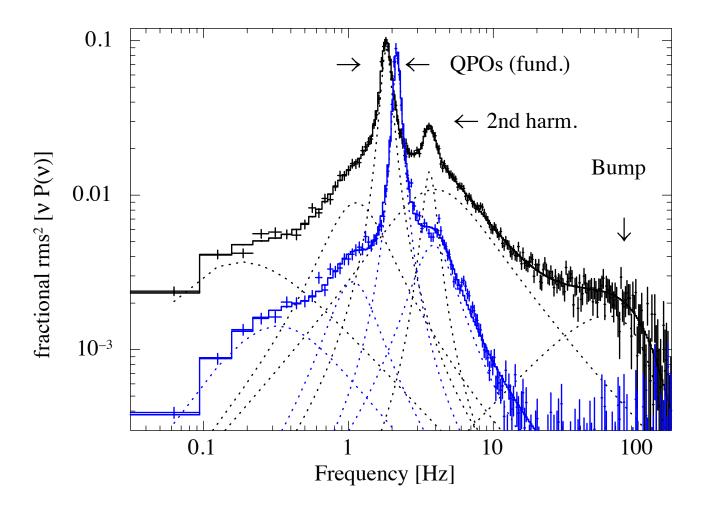
⁵While it is apparent to the eye from the Figure, it is difficult to quantify what a strong radio flare is. Here we classify a flare as strong if its flux density exceeds 50 mJy for more than 10 days and the flare lasts more than 100 days.

Taken together, the results shown in Extended Data Figures 8 and 9 and the sudden change of the feedback fraction 29,75 from ~ 1 to ~ 0 when the QPO frequency is, respectively, above or below 2 Hz are consistent with the scenario described earlier, in which the energy that is initially stored in the X-ray corona is gradually released into the radio jet and, quite possibly, the X-ray corona itself becomes the jet.

The morphing of the extended corona into the jet is strengthened by the relation between 412 the actual luminosity of the corona and that expected if the emission is due to inverse-Compton 413 scattering of seed photons from the accretion disc. In Extended Figure 10 we show the ratio of 414 the expected to the observed corona flux vs. the observed flux of the corona. We calculated the expected flux as the product of the bolometric disc flux times e^y , where y is the Compton parameter. (This is the expression for the case that the optical depth is $\tau > 1$.) Since the Compton y parameter gives the number of scatterings times the relative energy that a photon gains per scattering, if the seed-photon source is the disc, the expected and observed corona fluxes should be roughly the 419 same. This Figure shows that the observed and expected fluxes are the same (within a factor 3) 420 only when the lags of the QPO are negative (yellow, orange and red points), i.e., when the QPO 421 frequency is higher than \sim 2 Hz and the disc is enshrouded by the corona. When the lags are 422 positive (light blue and blue points) and the corona morphed into the jet, if the seed photons were 423 from the disc the expected flux of the corona is much lower than the one observed. In this phase a 424 different source must be providing the seed photons for Comptonisation. Since in this phase the jet 425 is active, the most likely source of seed photons is synchrotron emission⁷⁷ from the same electrons 426 that produce the jet. Indeed, if we calculate the expected corona flux by multiplying the observed 427

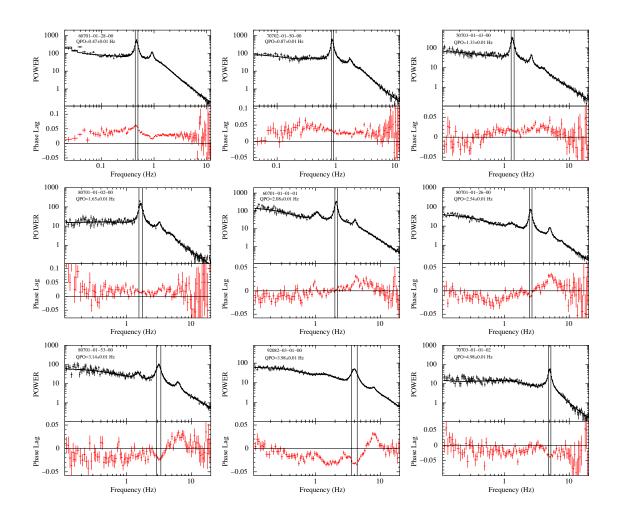
- synchrotron flux coming from the jet extrapolated to the X-ray band times e^y , the expected corona flux is much higher when the lags of the QPO are positive than when they are negative.
- Data availability All the X-ray data used in this study are available NASA's High Energy Astrophysics Science Archive Research Center https://heasarc.gsfc.nasa.gov/. The radio
 data used in this study are available through the website http://www.mrao.cam.ac.uk/
- Code availability The data reduction was done using HEADAS v6.27, while the model fitting
 of energy, power and lag-energy spectra was done with XSPEC; both packages are available at
 the HEASARC website (https://heasarc.gsfc.nasa.gov/). The timing analysis was
 performed with the GHATS package developed by T.M.B. and is available on request (http:
 //astrosat.iucaa.in/~astrosat/GHATS_Package/Home.html). All figures were
 made in TOPCAT, a JAVA-based scientific plotting package developed by Mike Taylor (http:
 //www.star.bris.ac.uk/~mbt/topcat/).

Extended data figures and tables

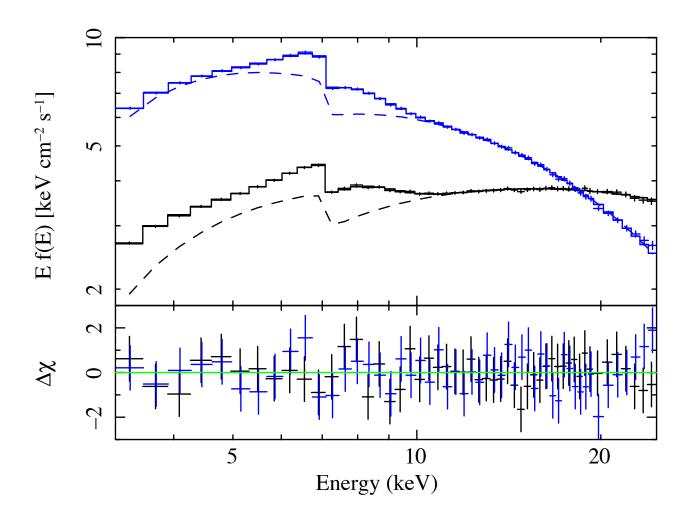


Extended Data Figure 5 Representative power spectra of GRS 1915+105

X-ray Fourier power spectra of two observations of GRS 1915+105 (data with errors) fitted with a model consisting of several Lorentzians (solid lines with the individual components indicated with dotted lines) for the QPO (plus harmonic and sub-harmonic components) and a zero-centred Gaussian for the high-frequency bump. In both power spectra the strong QPO fundamental component is at \sim 2 Hz; the high-frequency bump peaking at \sim 70 Hz is significantly detected, with an rms amplitude of $8.0\pm0.3\%$, in the power spectrum plotted in black (ObsID 30703-01-34-00 of September 21 1998), and is significantly absent, with a 95% confidence upper limit of the rms amplitude of 1%, in the power spectrum plotted in blue (ObsID 30402-01-09-01 of April 10 1998).

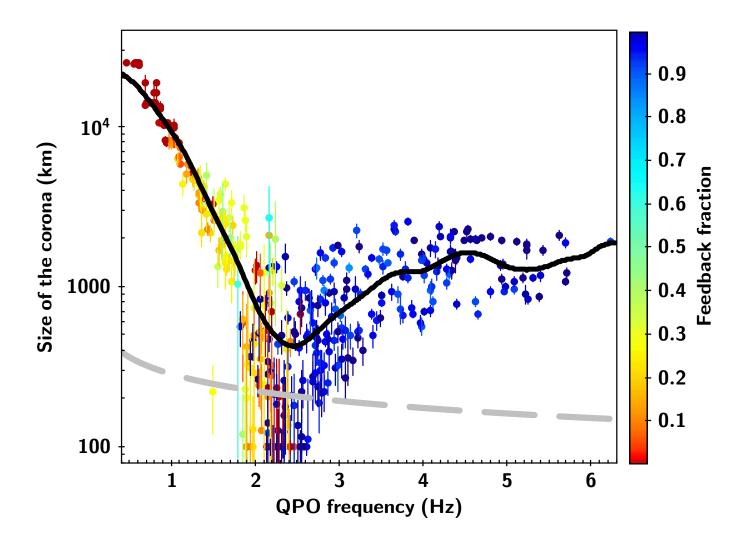


Extended Data Figure 6 Power-density (upper half of each panel) and phase-lag (lower half of each panel) spectra of nine observations of GRS 1915+105 with RXTE. Each panel corresponds to an observation in which the QPO was at the frequency given, together with the ObsID, in the legend of the panel. We calculated the power spectra using the photons from the full PCA band, and the phase-lag spectrum using photons in the 5.7-15 keV band with respect to the photons in the 2-5.7 keV band. The lags are given in units of rad/ 2π and indicate whether, at a given frequency, the variability of the low-energy photons lag (negative lags) or lead (positive lags) that of the high-energy photons. The black vertical lines indicate the range of frequencies that we used to measure the lags of the QPO.



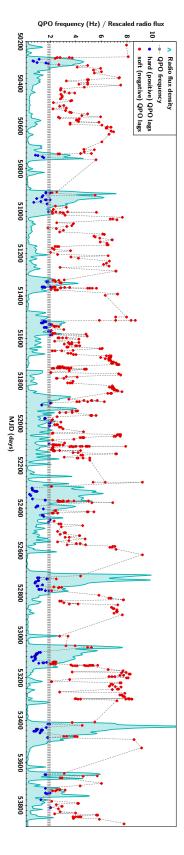
Extended Data Figure 7 Representative energy spectra of GRS 1915+105

X-ray energy spectra (data points with errors) of the same two observations of GRS 1915+105 shown in Extended Data Figure 5, fitted with a model consisting of the emission from the accretion disc, the corona and a broad iron line. The dashed lines represent the best-fitting model of the corona, while the solid lines through the data correspond to the full model. In the spectrum plotted in black (ObsID 30703-01-34-00 of September 21 1998) the temperature of the corona is $kT_{\rm e}{=}10.9{\pm}0.8$ keV, while in the one plotted in blue (ObsID 30402-01-09-01 of April 10 1998) $kT_{\rm e}{=}6.3{\pm}0.5$ keV. The difference in temperature between the two spectra is apparent by the fact that, at high energies, the flux drops quicker in the spectrum plotted in blue than in the one plotted in black. The bottom panel shows the residuals, $\Delta\chi{=}({\rm data-model})/{\rm error}$, of the best-fitting model.

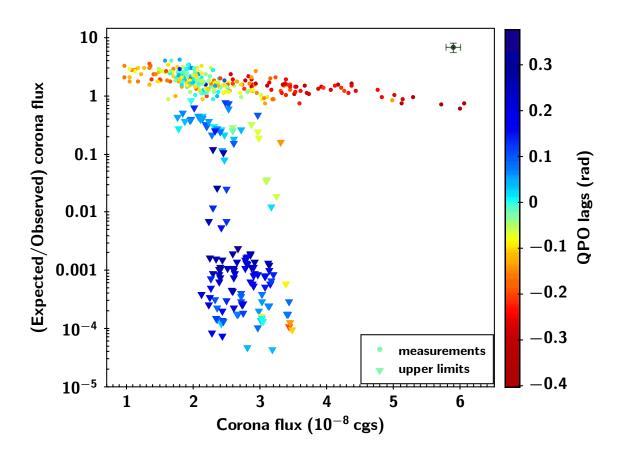


Extended Data Figure 8 Size of the corona as a function of QPO frequency for GRS 1915+105

Each point corresponds to one of the 410 observations of GRS 1915+105. The size of the corona comes from the fits of a variable-Comptonisation model^{28,29} to the rms and lag spectra of the QPO⁷⁵. The colour of the points indicates the feedback fraction, the fraction of photons from the corona that returns to the disc. The black solid line is the weighted average of the points. The grey dashed line shows the inner radius of the accretion disc in km assuming that the QPO frequency is the Lense-Thirring precession frequency for a 12 solar-mass black hole.



Extended Data Figure 9 Time evolution of QPO frequency and radio flux for GRS 1915+105. The points connected by a line show the time evolution of the frequency of the QPO in the X-ray power spectrum of GRS 1915+105. The light-blue curve (smoothed with a Gaussian kernel) shows the simultaneous measurements of the radio flux density at 15 GHz (y axis rescaled). A strong radio flare appears whenever the lags of the QPO turn from soft (red points) to hard (blue points), corresponding to the QPO frequency crossing from above to below \sim 2 Hz. The horizontal band shows the range of QPO frequencies over which the transition occurs. The probability of having a positive QPO lag *always* and *only* during a radio flare if the two phenomena were uncorrelated is less than 2×10^{-10} . (Fig. 4 in the main text shows a zoom-in of the first two flares.)



Extended Data Figure 10 Expected corona flux in GRS 1915+105

Ratio of the expected to the observed corona flux vs. observed corona flux. The expected corona flux is calculated as the bolometric disc flux times e^y , where y is the Compton parameter. Each point corresponds to one of the 410 observations of GRS 1915+105. The average error of the plotted quantities is shown at the upper right of the plot. The colour scale represents the phase lags, in units of $(\text{rad}/2\pi)$, of the QPO (see Fig. 2 for an explanation). The triangles indicate upper limits of the ratio of the expected to the observed corona flux. The expected and observed fluxes are roughly the same (within a factor of \sim 3) when the lags are negative, the corona is extended and hot, and it covers the inner parts of the accretion disc (colours towards red), whereas the expected flux drops significantly when the lags are positive, the geometry of the corona changes and its temperature drops as it turns into the jet (colours towards blue).

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