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Dheeraj R. Pasham  
*Massachusetts Institute of Technology, dheeraj@space.mit.edu*

Ronald A. Remillard  
*Massachusetts Institute of Technology*

P. Chris Fragile  
*College of Charleston*

Alessia Franchini  
*University of Nevada, Las Vegas, alessia.franchini@unlv.edu*

Nicholas C. Stone  
*Columbia University*

*See next page for additional authors*

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A Loud Quasi-Periodic Oscillation after a Star is Disrupted by a Massive Black Hole

Dheeraj R. Pasham1*, Ronald A. Remillard1, P. Chris Fragile2, Alessia Franchini3, Nicholas C. Stone4, Giuseppe Lodato5, Jeroen Homan6,7, Deepto Chakrabarty1, Frederick K. Baganoff1, James F. Steiner1, Eric R. Coughlin4, Nishanth R. Pasham8

1Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
2Department of Physics and Astronomy, College of Charleston, Charleston, SC 29424, USA
3Department of Physics and Astronomy, University of Nevada, Las Vegas, NV 89154, USA
4Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
5Dipartimento di Fisica, Universita degli Studi di Milano, Milan 20133, Italy
6Eureka Scientific, Inc., Oakland, CA 94602, USA
7SRON, Netherlands Institute for Space Research, Utrecht, 3584 CA, The Netherlands
8Allyo, Mountain View, CA, USA

*To whom correspondence should be addressed; E-mail: dheeraj@space.mit.edu

The tidal forces close to massive black holes can rip apart stars that come too close to them. As the resulting stellar debris spirals towards the black hole, it heats up and emits x-rays. We report the observations of a stable 131-second x-ray quasi-periodic oscillation from the tidal disruption event ASASSN-14lii. Assuming the black hole mass indicated by host galaxy scaling relations implies that, (i) this periodicity originates from close to the event horizon, and (ii) the black hole is rapidly spinning. Our findings demonstrate that tidal disruption events can generate quasi-periodic oscillations which encode information
about the physical properties of their black holes.

Almost all massive galaxies are thought to harbor a massive black hole (MBH; masses $\gtrsim 10^4$ solar masses, $M_\odot$) at their centers (1), yet most of them are inactive and do not produce any observable electromagnetic radiation. However, roughly once every $\sim 10^4$–$10^5$ years a star is predicted to pass near enough to the black hole (BH) to be disrupted by the BH’s gravitational forces (2–4). Such episodes, known as tidal disruption events (TDEs) (5), trigger accretion of the debris onto quiescent BHs and provide a brief period of activity. This gives an opportunity to measure the two properties that characterize BHs: mass and spin. Empirical scaling laws can be used to infer BH masses, for example, using host galaxy properties (6), but the spins of MBHs have been difficult to constrain. This is because the effects of spin predicted by Einstein’s general theory of relativity are negligible except in the immediate vicinity of BHs, typically within a few gravitational radii (7). One gravitational radius is $R_g = GM/c^2$, where $G$, $M$, and $c$ are the gravitational constant, BH mass, and the speed of light, respectively. Measuring BH spins requires observations of radiation from the innermost regions of the accretion flow, where gravity is strong. Theoretical models of TDEs predict that shortly after the disruption, a fraction of the stellar debris settles into a hot inner disk with peak thermal emission in the soft x-rays or extreme ultra-violet (UV) (8). Identifying such disk-dominated/x-ray bright TDEs could be used to determine MBH spins.

The transient event ASASSN-14li was detected by the All-Sky Automated Survey for Supernovae (ASASSN) on 22 November 2014 (3). It exhibited most properties of previously-known TDEs: a spatial position consistent with the host galaxy’s center (within 160 parsecs (3)), a luminosity declining in time with a powerlaw index of $\frac{5}{3}$ (9) as expected for a TDE (10), a blue optical spectrum with broad Hydrogen and Helium emission lines and a constant optical color, unlike an ordinary supernova (3). ASASSN-14li also produced x-rays (9) and a radio synchrotron flare (11, 12).
The masses of central MBHs are known to correlate with the properties of their host galaxies (6, 13). The velocity dispersion of stars in the inner bulges of galaxies ($\sigma_{\text{vel}}$) is correlated with the BH mass ($M$), commonly referred to as the $M$-$\sigma_{\text{vel}}$ relation (6, 13). The total stellar mass in the bulge and the optical luminosity of the host galaxy are also known to correlate with the BH mass (13). These empirical relations indicate that the BH in ASASSN-14li has a mass in the range $10^{5.8-7.1} M_\odot$ (3,12,14). This range is consistent with BH mass derived independently from physical modeling of ASASSN-14li’s multi-wavelength light curves (9). The observed x-ray energy spectrum is blackbody-like (thermal) (9,15,16) with peak 0.3-1.0 keV luminosity of a few $\times 10^{43}$ erg/sec (Fig. 1). The inferred size of the thermal x-ray emitting region ($\sim 10^{12}$ cm) is only a few gravitational radii (9) and remains roughly constant with time (9, 15). This suggests that x-rays from ASASSN-14li originate from an inner accretion flow close to the BH.

In stellar-mass BHs, a sudden onset of accretion often excites quasi-periodic oscillations (QPOs) in the x-ray flux (17). In instances where the x-ray emission is dominated by the accretion disk, observed QPO frequencies have been used to measure the BH spins (18,19). We searched for a stable QPO in the soft x-ray band (0.3-1.0 keV) observations of ASASSN-14li by combining publicly-available data from the $XMM$-$Newton$ and $Chandra$ X-ray observatory space telescopes. We extracted the average power density spectrum (PDS) from data taken at six epochs during the 450 d after ASASSN-14li’s discovery (Fig. 1). The combined x-ray PDS shows a feature at 7.65±0.4 mHz (131-seconds; coherence, $Q = \text{centroid-frequency}/\text{QPO’s-width}=16\pm6$), shown in Fig. 2. The highest bin in the QPO is statistically significant at the 4.8$\sigma$ level for a search at all frequencies (trials) below 0.5 Hz (Fig. 2A) under the white noise hypothesis (variability is independent of timescale). While the data is consistent with white noise, by assuming the most extreme red noise allowed by the data, i.e., noise scales inversely with frequency, we derive a conservative lower limit on the statistical significance (false alarm probability) to be 3.9$\sigma$ (or $10^{-4}$; (20)).
The QPO is independently detected in the \textit{XMM-Newton} and \textit{Chandra} datasets with a significance of \(\approx 4\sigma\) and \(\gtrsim 2.6\sigma\), respectively, for a search including all frequencies/trials below 0.5 Hz (20) (Fig. S9). We estimated the QPO’s fractional root-mean-squared (rms) amplitude during the last \textit{XMM-Newton} epoch to be \(4\pm1\%\) (Fig. 1; (20)). Because the source was bright and the instrument readout was not fast enough in the first four \textit{XMM-Newton} observations, the data was piled-up (20). Thus, similar measurements could not be made for epochs X1-X4. The \textit{Chandra} observation was made roughly 420 d after the discovery, by which time ASASSN-14li’s flux had declined by \(\approx 10\), reducing the pile-up (20). The QPO’s fractional rms amplitude in \textit{Chandra} data was \(59\pm11\%\) (Fig. 3; (20)). This suggests that between X5 and C1, separated roughly by 50 days, the fractional rms amplitude of the QPO increased by at least an order of magnitude. After establishing the QPO at 7.65 mHz, we also constructed an average x-ray (0.3-1.0 keV) PDS from observations taken by the Neil Gehrels \textit{Swift} observatory. The strongest feature in the average \textit{Swift} PDS is at 7.0\(\pm0.5\) mHz, consistent with the QPO detected in the \textit{XMM-Newton} and \textit{Chandra} datasets (Fig. 2B).

Plotting the \textit{Chandra} data in imaging mode shows only a single x-ray point source spatially coincident with the galaxy LEDA 043234 (Fig. S5). This demonstrates that the QPO does not originate from a nearby contaminating source. The QPO is detected by three different x-ray detectors, establishing that it is not an instrumental artifact but associated with ASASSN-14li. Movie S1 shows that the QPO signal improves gradually as more power spectra are averaged, implying that the QPO does not originate from a single epoch observation but is present throughout at least the first 450 d of the event. The average \textit{Swift} PDS using data acquired over 500 d, the \textit{Chandra} PDS from roughly day 420, and the average \textit{XMM-Newton} PDS all show QPOs at a consistent frequency throughout the first 450 d of the outburst. This implies that the QPO is stable for \(3\times10^5\) cycles (\(\approx 450\) d/131 s). While the stability and coherence of the QPO are similar to the QPOs of stellar-mass BHs in disk-dominated state, the modulation amplitude of
>50% (Fig. 3) is higher (e.g., (21)).

An alternative scenario in which the oscillation might be a neutron star pulsation is unlikely for multiple reasons: the large x-ray, optical/UV and radio photospheric sizes (3,15,16,22), high bolometric luminosity (15, 16), and the very soft x-ray spectrum (9, 15). In general, the multiwavelength properties of ASASSN-14li are similar to many previously-known TDEs, unlike any known neutron star outburst (see Supplementary Text).

Assuming ASASSN-14li’s BH mass range implied from standard host galaxy scaling relations, we compared the 7.65 mHz QPO frequency to the five possible frequencies of motion of a test particle orbiting a spinning BH (7, 19). The five frequencies are determined by the BH’s mass, spin and the radial distance of the emitting region (Supplementary Text). In disk-dominated stellar-mass BHs the inner edges of the accretion disks extend to a constant radius for a wide range in accretion rates (e.g., (23)). The natural inner radius predicted by general relativity is the innermost stable circular orbit (ISCO), which depends on BH spin. Because ASASSN-14li appears to be disk-dominated we started our frequency comparison using the ISCO as the radial distance (Fig. 4). Even at this closest possible location, the only possible solutions are those with a rapidly spinning BH. A lower limit on the BH’s dimensionless spin parameter ($a^*=Jc/GM^2$, where $J$ is BH’s angular momentum) can be calculated from the BH spin vs mass contours shown in Fig. 4. This corresponds to the intersection of the BH mass lower limit and the fastest frequency, which at any given radius is the Keplerian frequency. This implies that ASASSN-14li’s spin parameter is greater than 0.7 (Fig. 4). Placing the test particle at any larger radius would only shift this limit to higher spin values. At any given radius as the other four frequencies (Fig. 4; Supplementary Text) are below the Keplerian value, associating the QPO with them would again shift the spin limit to higher values.

If we ignore frequencies higher than the azimuthal (Keplerian) frequency (but see below), then we can interpret Fig. 4 as showing a lower limit on the spin (e.g., (24)) of the MBH that
caused the TDE. Alternatively, we can interpret the figure as an upper limit of $2 \times 10^6 M_\odot$ on the black hole mass for a maximum astrophysically plausible spin of $a^* = 0.998$ (25). The maximal spin comes from the conjecture that naked singularities (such as BHs with $a^* > 1$) are not allowed to exist in nature (26) and the reality that counter-torques from radiation absorbed into the BH limit the growth of $a^*$ to 0.998 (25).

It is possible that ASASSN-14li’s host galaxy and the disrupting BH may not obey the empirical scaling laws (27) and instead the BH mass could be below a value of a few $\times 10^5 M_\odot$. If so, then the BH could have a moderate spin, but it would imply that it is an intermediate-mass black hole, a class of objects whose existence has been controversial (e.g., see (28–30)).

The QPO has a higher dimensionless frequency than those those measured from stellar-mass black holes (17), $\text{QPO-frequency}/(c^3/GM) > 0.024$, where we have used the lower limit of the estimated BH mass range (14). In stellar-mass BHs the dimensionless QPO frequencies are $\lesssim 0.01$ (17). This implies that the radiating material producing the QPO is located close to the BH’s event horizon, and rules out alternative models for x-ray radiation that require an emitting region far away from the black hole. The physical mechanism that produced the QPO remains unclear (Supplementary Text).

The QPO in ASASSN-14li has further differences from those arising from stellar-mass BHs. The high-frequency QPOs (frequencies of a few $\times 100$ Hz) of accreting stellar-mass BHs are seen only in hard x-rays ($> 2$keV) (17) and not in disk-dominated states (21), whereas ASASSN-14li’s energy spectrum is very soft (9). The rapid rise in the QPO’s rms amplitude is also unlike stellar-mass BHs. ASASSN-14li’s QPO may represent a different disk oscillation mode to other systems, and thus it may not be valid to directly compare it with known QPOs of stellar-mass BHs.

A quasi-periodicity (at $\approx 200$ s) was previously reported from the TDE SwiftJ164449.3+573451 (SwJ1644+57; (31)). However, SwJ1644+57 is an atypical TDE in
which the entire electromagnetic radiation was dominated by a jet directly pointing along our line of sight (e.g., (32)). Radio followup indicates that only a small fraction of thermal TDEs launch collimated jets (33), and only a small fraction of such jets would align with our line of sight. Compared to ASASSN-14li, SwJ1644+57’s periodicity was roughly 15 times weaker in amplitude and was present only for a short duration of at most a few weeks after its discovery.

High frequency x-ray QPOs originate from the strong gravity regime in the immediate vicinity of BHs. The stable period of the QPO in ASASSN-14li suggests that it is tied to the physical properties (mass and spin) of the BH at the heart of the disruption.
Figure 1: **ASASSN-14li’s long-term x-ray light curve.** The data were taken with Swift (pile-up corrected: (20)). The dashed vertical lines represent the five epochs of *XMM-Newton* observations (blue, labelled X1 to X5), and one epoch of *Chandra* observation (red, labelled C1).
Figure 2: **X-ray power spectra for ASASSN-14li, showing a QPO at 7.65 mHz.** (a) The average x-ray PDS from eight continuous 10,000 s light curves taken with *XMM-Newton* and *Chandra*. The frequency resolution is 0.8 mHz. The strongest feature in the power spectrum lies at a frequency of 7.65±0.4 mHz (∼131-seconds). The dashed horizontal blue, magenta, and red lines represent the 3, 4, and 5σ white noise statistical thresholds. The data surrounding the QPO feature are consistent with white noise (20) but we also estimated the QPO significance under red noise, finding that it’s highest bin is significant at at least the 3.9σ level (20). ±1σ uncertainties are shown with grey error bars. Fig. S9 shows the *XMM-Newton* and *Chandra* data separately. (b) Average *Swift* PDS from 85 continuous 1000 s light curves with a frequency resolution of 1 mHz. The horizontal line shows the 3σ threshold assuming a single trial search at 7.65 mHz. The highest peak in the power spectrum is at 7.0±0.5 mHz, consistent with the *XMM-Newton* and the *Chandra* power spectra (Fig. S9).
Figure 3: **ASASSN-14li’s folded x-ray light curve using Chandra data.** The fold period during epoch C1 was estimated by oversampling the light curve (20) to be 134.6±0.1 s (or 7.43±0.006 mHz). The best-fitting sinusoidal (dashed red) curve implies a fractional amplitude of 35±8%, consistent (within the 90% confidence limits) with the estimate from the PDS (Fig. S9). The zero phase is arbitrary and two cycles are shown for clarity. ±1-σ uncertainties are shown as grey error bars. Figs. S10 and S11 show the folded XMM-Newton light curves and the evolution of the QPO’s rms amplitude, respectively.
Figure 4: **Black Hole dimensionless spin parameter vs mass contours:** Spin vs mass contours assuming the 7.65 mHz QPO is associated with any of three particle frequencies: Keplerian frequency ($\nu_\phi$, blue), vertical epicyclic frequency ($\nu_\theta$, magenta) and Lense-Thirring precession ($\nu_\phi - \nu_\theta$, green) at the innermost stable circular orbit (ISCO). At the ISCO the radial epicyclic frequency ($\nu_r$) is zero and the periastron precession frequency ($\nu_\phi - \nu_r$) is thus equal to the Keplerian frequency (20). The widths of these contours reflect the QPO’s width of 0.7 mHz (upper limit). The dotted horizontal lines show ASASSN-14li’s BH mass range ($10^{5.8-7.1} M_\odot$) estimated from its host galaxy scaling relations. Within this mass range, the only formal solutions are the ones that require the BH spin parameter to be greater than 0.7.
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20. Material and methods are available as supplementary materials.


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Supplementary Materials.

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Materials and Methods.

1 Data Reduction.

The data used in this work has been acquired by three different x-ray telescopes: Swift, XMM-Newton, and Chandra. The X-Ray Telescope (XRT) on board Swift started monitoring ASASSN-14li roughly a week after its discovery by the All-Sky Automated Survey for Supernovae (ASAS-SN (34)) on Modified Julian Date (MJD) 56983.6 (3). Since discovery on 22 November 2014 until May 2017, Swift observed ASASSN-14li on over 100 occasions with each observation lasting between a few × (100-1000) seconds. We used obs IDs ranging from 00033539001 to 00033539097. XMM-Newton and Chandra—with effective areas larger than the XRT—provided fewer but more sensitive observations each lasting anywhere between 10,000 and 90,000 seconds. Logs of observations are provided in Table S1.

We started our analysis with Swift/XRT data to assess the long-term x-ray evolution as follows. As noted by earlier works (9, 16), the individual XRT data sets suffer from pile-up. To mitigate the effect of pile-up we extracted event lists from an annulus region centered on the source by excluding an inner pile-up radius in each individual observation, following the procedure outlined by the XRT pile-up guide at http://www.swift.ac.uk/analysis/xrt/pileup.php. The individual XRT observations only have a few counts and thus cannot be used to constrain the spectral shape. Therefore, we extracted average energy spectra by combining neighboring observations until a total of ~3500 counts were reached. Similar to earlier works (9) we modeled each energy spectrum with an absorbed black body (phabs*bbodyrad) modified by the red-shift of the host galaxy (zshift), and implemented it in the x-ray spectral fitting package, XSPEC (35), as phabs*(zshift(phabs*bbodyrad)). The first phabs accounts for the Milky Way absorption along the line of sight in the direction of ASASSN-14li. We estimated the flux and thus the luminosity in each individual Swift observation by fitting it with the same black body function but limited the column density and the disk temperature values to the nearest (in time) averaged spectral values (see (22) for more specific details and the best-fit model parameters). ASASSN-14li’s final XRT x-ray (0.3-1.0 keV) long-term light curve is shown in Fig. 1.

XMM-Newton and Chandra observed ASASSN-14li on multiple occasions with six and three data sets publicly available at the time of analysis. However, one of the XMM-Newton observations (obsID: 0770980501) was severely affected by background flaring and two of the Chandra data sets carried out with the High-Resolution Camera (HRC) were background dominated. Therefore, we did not consider these data sets for further analysis. After this initial screening we were left with five XMM-Newton and one Chandra observation. The vertical lines in Fig. 1 mark the epochs of these observations. A summary of these observations can be found in Table S1.

We used the XMM-Newton Standard Analysis System (xmmmsas: version 15.0.0) to extract the images and the event lists from all the five XMM-Newton data sets. Because the detection
sensitivity of a quasi-periodic feature in the light curves increases sharply with the count rate \((36)\), we combined the data acquired by all the three detectors (named pn, MOS1 and MOS2) on the European photon imaging camera (EPIC) and considered only those epochs during which all the three detectors were operating. We started our analysis by reducing/reprocessing the datasets to extract the level-2/cleaned event-lists. We first extracted images of ASASSN-14li’s field of view and visually confirmed that there are no contaminating sources nearby. We extracted source events from a circular region of radius 40\arcsec centered on the source. All the observations were taken in a small window mode to enable faster readout. To better constrain the background variability, events were extracted from four circular regions offset from the source and with radii of 58\arcsec, 45\arcsec, 32.5\arcsec, and 32.5\arcsec. A sample XMM-Newton/EPIC (pn+MOS) image is shown in Fig. S1 highlighting the source and the background extraction regions. A large fraction of these data sets were affected by background flaring. Because these high-amplitude background flux variations can sometimes manifest as quasi-periodic features in the power spectra we carefully removed these high background flux epochs from our analysis. This—combined with our requirement to consider only times when all the three (pn+MOS1+MOS2) detectors were active—resulted in a number of Good Time Intervals (GTIs) in each individual observation (Figs. S2A,C,E and S3A,C).

Earlier studies \((9, 37)\) have found that ASASSN-14li is piled-up even in the XMM-Newton observations. Following the standard procedure to check for pile-up, as outlined in the XMM-Newton data analysis guide \((38)\), we also reach the same conclusion. Fig. S4 shows the output from the `xmmmsas task epatplot` for the EPIC-pn detector for all the five observations \((Xn, n \text{ from } 1 \text{ to } 5 \text{ as marked in Fig. 1})\). The plots show the migration of X-ray events to higher patterns, i.e., from single to double, because of pile-up. When pile-up occurs the detector incorrectly interprets multiple single pixel events in adjacent pixels as a single multi-pixel event. This results in a deficit of single pixel events and an excess of double (or higher) pixel events as seen in Fig. S4. For a given detector, the expected fraction of total X-ray events that create a charge cloud pattern within \(i\) (= single, double, etc) pixels usually depends on the energy as can be seen from the solid curves in Fig. S4. The disagreement between the expected and the observed distributions of the single and the double pixel events suggests that the observations are indeed piled-up. While the observed count rates are well below the pile-up threshold count rates given in the XMM-Newton calibration documents \((39)\), pile-up does occur (Fig. S4), and this may be due to the soft spectrum of ASASSN-14li \((37)\).

For the purposes of variability studies, pile-up can have two major effects: (i) it reduces the overall count rate, and (ii) it may reduce the fractional root mean-squared (rms) amplitude \((40)\). Simulations have shown that the fractional rms amplitude of piled-up Chandra x-ray data of the transient XTE J1650-500 were reduced by roughly 1% \((41)\). With regards to detecting a periodic/quasi-periodic signal, even though the mean rate is reduced, the count rate at the peak of the waveform is reduced slightly more than at the trough, resulting in a reduced fractional rms \((42)\). To alleviate the pile-up issue and at the same time not compromise too much on the count rate, we considered all events within a 40\arcsec circular region for power spectral analysis.

Because ASASSN-14li’s energy spectrum is very soft the count rates in 1-10 keV band are
negligible compared to the 0.3-1.0 keV range. We estimated the ratio of 1.0-10.0 keV to 0.3-1.0 keV background subtracted source count rates in the five XMM-Newton obsIDs 0694651201, 0722480201, 0694651401, 0694651501, and 0770980101 to be 0.009, 0.002, 0.001, 0.003, and 0.005, respectively. In other words, ASASSN-14li’s 1-10 keV flux is less than 1% of 0.3-1.0 keV flux, and is dominated by the background. A similar conclusion was reached by earlier works (15). Therefore, we only considered the soft 0.3-1.0 keV events for power analysis. XMM-Newton data analysis guide (43) recommends the use of single pixel events PATTERN==0 for piled-up data. Therefore we added an additional filter to only include single pixel events.

We then extracted an image and an event list from Chandra’s Advanced CCD Imaging Spectrometer (ACIS) using the Chandra Interactive Analysis of Observations tool ciao. Chandra has better spatial resolution than XMM-Newton and Swift. We inspected the ACIS image of ASASSN-14li which has a spatial resolution of 0.5″–and found that it is the only source in that field of view (Fig. S5). Source events were extracted from a circular region of radius 2.5″ centered on the source while the background events were extracted from a region much (≳ 3000 times) larger than the source region. Again we utilized only single pixel events in the calibrated energy range of 0.4-1.0 keV.

2 Power Spectral Analysis.

We first divided the data into 10,000-second continuous segments and extracted their light curves with a 1-second time resolution. Because the individual observations (see Table. S1) were broken into several GTIs this selection resulted in a total of eight uninterrupted data segments. The epochs of these eight 10,000 s light curves, i.e., the start and the end times in units of seconds since modified Julian date (MJD) of 50814.0, are shown in Figs. S2 and S3 and tabulated in Table S2. We then constructed a Leahy normalized (44) power density spectrum (PDS)–where the mean Poisson noise level is 2–from each of these 10,000 second light curves. This resulted in eight PDS which were all combined to obtain an average PDS of ASASSN-14li. This is provided as a supplementary data file. The resulting PDS contains a quasi-periodic oscillation (QPO) candidate at roughly 7.65 mHz.

2.1 Underlying Noise Distribution:

The statistical significance of a power fluctuation in a PDS depends on the underlying distribution of the noise powers. Except at 7.65 mHz (± 1 frequency bin), which is dominated by the QPO, the rest of the PDS between 0.001 and 0.5 Hz are roughly constant with no obvious dependence on frequency, i.e., the noise appears to be white. A statistical test for white noise is a test of whether the powers are \( \chi^2 \) distributed (36).
2.1.1 Probability plot:

As a first step, in order to visually assess whether the noise powers in the vicinity of the QPO candidate follow a $\chi^2$ distribution, we constructed a $\chi^2$ probability plot using the noise powers in the frequency bins between 0.001 and 0.1 Hz. We excluded the three bins containing the signal itself at 7.65 mHz. The resulting plot is shown in Fig. S6. A probability plot is a commonly used statistical tool that shows the theoretical quantiles of the assumed distribution against the ordered sample values, i.e., noise powers in our case. We used Filliben’s (45) formula for estimating the theoretical quantiles. In our case the distribution is $\chi^2$ with $2 \times 8 \times 8$ degrees of freedom (dof) scaled by a factor of 1/64. This particular $\chi^2$ distribution was used because we averaged in frequency by a factor of 8 and averaged 8 individual power spectra. If the data lie on a straight line then it indicates that they are consistent with the theoretical distribution. It is evident from Fig. S6 that the data points on the probability plot follow a straight line and thus appear consistent with a $\chi^2$ distribution with 128 dof scaled by a factor of 1/64.

2.1.2 Comparing powerlaw + constant vs constant models for the continuum.

As a check, we fitted the Leahy-normalized power spectrum in Fig. 2A with a constant plus a Lorentzian for the QPO and compared the improvement in $\chi^2$ by adding a powerlaw. The former yielded a $\chi^2$ of 98 for 121 dof while a model with powerlaw resulted in a $\chi^2$ of 94 for 119 dof. Repeating the same exercise on the unbinned PDS, i.e., before averaging 8 neighboring bins (lowest frequency of $10^{-4}$ Hz), resulted in $\chi^2$ values of 1082 (996 dof) and 1077 (994 dof) for the former (constant+QPO) and latter (powerlaw+constant+QPO) models, respectively. In summary, the improvement in $\chi^2$ was limited, and thus a powerlaw component is not statistically required by the data.

2.1.3 Kolmogorov-Smirnov and Anderson-Darling goodness of fit tests:

We also performed the Kolmogorov-Smirnov (K-S) and Anderson-Darling goodness-of-fit tests under the null hypothesis that the noise powers between 0.001 and 0.1 Hz, excluding the three bins of the QPO candidate, are $\chi^2$ distributed with $2 \times 8 \times 8$ dof scaled by a factor of 1/8/64 (36). In other words, the null hypothesis is that the underlying noise is white. We choose an upper limit of 0.1 Hz to ensure the sample is not biased by higher (>0.1 Hz) frequencies.

Before evaluating the K-S and Anderson Darling tests, we computed the empirical distribution function (EDF) and the probability density function (PDF) of the noise powers. These are shown in Fig. S7A along with the expected $\chi^2$ distribution. Again, it can be seen that the data track the expected $\chi^2$ distribution.

We then computed the K-S test statistic using the EDF. Thereafter, we generated bootstrap simulations to compute the distribution of the K-S test statistic itself as follows. The distribution of the test statistic is necessary to reject or not to reject the null hypothesis. First, we randomly draw the same number (=122) of elements as the observed noise powers from a $\chi^2$ distribution with 128 dof. Then we evaluate its EDF and scale it by a factor of 1/64, just like the real data.
Finally, we compute the K-S test statistic and store its value. We repeat this process 10,000 times to get a distribution of the K-S test statistic for a $\chi^2$ distribution with 128 dof for a given sample size of $N_{\text{sample}} (=122)$. This bootstrap method accounts for the size of the sample. The resulting distribution is shown as a blue histogram in the bottom left panel of Fig. S7C. ASASSN-14li’s observed K-S test statistic is close to the median value of the distribution. This suggests that noise powers are very much consistent with the expected $\chi^2$ distribution, i.e., ASASSN-14li’s noise powers in the vicinity of the QPO candidate signal are consistent with being white.

We also investigated the goodness-of-fit with the Anderson-Darling test. We computed the distribution of the test statistic using the same bootstrap technique described above. This resulting distribution is shown in Fig. S7D. Again, the value of Anderson-Darling’s test statistic indicates that the observed noise powers of ASASSN-14li’s PDS are consistent with being $\chi^2$ distributed.

We also repeated the above tests by changing the frequency upper limit from 0.1 to 0.2 and 0.5 Hz. All of them lead to the same conclusion that the noise powers above 0.001 Hz are consistent with being white.

### 2.1.4 Statistical Significance under white noise:

We estimate the statistical significance of the feature at 7.65 mHz under the white noise hypothesis as follows. First, we ensured that the mean noise level was equal to 2 as this is the value expected from pure Poisson (white noise) process. We then computed the probability, at the 99.73% ($3\sigma$), the 99.9937% ($4\sigma$), and the 99.9999426697% (or $5\sigma$) confidence levels, of obtaining the power, $P = P_\ast \times 8 \times 8$ from a $\chi^2$ distribution with $2 \times 8 \times 8$ degrees of freedom. Here $P_\ast$ is the power value of a statistical fluctuation at a given confidence level. As mentioned above this $\chi^2$ distribution was used because we averaged in frequency by a factor of 8 and averaged 8 individual power spectra. Considering all the trials below 0.5 Hz we computed the $3\sigma$ ($1/(371 \times \text{trials})$), the $4\sigma$ ($1/(15787 \times \text{trials})$) and the $5\sigma$ ($1/(1744278 \times \text{trials})$) confidence contours (Fig. 2). The highest bin in the feature at 7.65 mHz is significant at the $4.8\sigma$ confidence level.

### 2.2 Statistical Significance under red noise:

The analysis above suggests that ASASSN-14li’s observed power spectrum within the frequency range of 0.001-0.5 Hz is consistent with white noise. However, it is still plausible that a weak/unknown red noise component is present in the data. To estimate the strength of the red-noise component, we fitted the unbinned PDS with a powerlaw + constant + QPO model. We choose the unbinned PDS as it allows us to access information at frequencies as low as $10^{-4}$ Hz. The best-fitting powerlaw normalization and index values were only poorly constrained to be $(1.2 \pm 4.5) \times 10^{-4}$ and $-1 \pm 0.4$, respectively. To test the significance of the QPO under red noise, we estimated the best-fitting normalization of the powerlaw component by fixing the index at various values between -0.3 and -1.7 ($\approx 95\%$ confidence interval). The resulting normalization
For each powerlaw index ($\alpha_0$; in -0.3, -0.7, -1.0, -1.4, -1.7) and its corresponding upper limit on the normalization, i.e., best-fitting normalization + uncertainty on the best-fitting normalization ($N_*$; see Table. S3), we employed the following Monte Carlo approach to estimate the global statistical significance of the QPO:

1. Using the algorithm described by Timmer & Koenig (1995) (46) we simulated $8 \times 50,000$ Leahy-normalized red noise light curves whose PSD is defined by ($\alpha_0$, $N_*$). Each of the light curves were 500,000 s in length, i.e., a factor of 50 longer than the length of the light curves used in ASASSN-14li’s PSD (Fig. 2). From each of these $8 \times 50,000$ simulated light curves we extracted 10,000 s segments from the center in order to account for red noise leakage (47). The light curves were sampled with a resolution of 1-s similar to ASASSN-14li’s data. Leahy power spectra were extracted and sets of 8 PDS were combined to obtain an average PDS. Finally, we averaged 8 neighboring bins in each of the 50,000 power spectra obtained from averaging 8 individual PDS. This gave us 50,000 simulated power spectra described by a given red-noise and that are sampled and averaged the same way as real data. We used Amazon web services for multiprocessing.

2. In order to carry out a global search for a signal below 0.5 Hz, we employed a methodology similar to Benlloch (2001) (48). We first divide each of the 50,000 simulated PDS ($P_i$, $i = 0, 1 \ldots 49999$) with the average of all the 50,000 simulated power spectra ($\langle P_i \rangle$). Then for each of the normalized (simulated) PDS we note down the maximum power spectral feature below 0.5 Hz, $\xi_{\text{max}} = \max \left[ P_i / \langle P_i \rangle \right]$. This way we emulate a “global” search that includes all frequency bins (trials) below 0.5 Hz and also properly accounts for red-noise.

3. We then estimate $\xi_{\text{max}}$ for the observed data in Fig. 2, $\xi_{\text{max,obs}}$, by simply dividing the observed PDS by $\langle P_i \rangle$.

4. Finally, using the 50,000 values of $\xi_{\text{max}}$ we computed (1.0 minus the cumulative distribution function) plot, i.e., the probability to exceed a given $\xi_{\text{max}}$ value, and compare that with the observed QPO’s value, i.e., $\xi_{\text{max,obs}}$. The results are shown in Fig. S8.

In all cases, the observed QPO value is significant at greater than at least $10^{-4}$ or the $3.9\sigma$ level. The reported significance values should be considered as the lower limits as they correspond to the upper limits of best-fitting red-noise normalizations (see Table S3).

### 2.3 Separate XMM-Newton and Chandra PDS.

After establishing the QPO at 7.65 mHz we extracted an average PDS separately from XMM-Newton and Chandra data. These are shown in Fig. S9. The 7.65 mHz QPO is evident in both the detectors and is significant at the $\approx4\sigma$ and $\gtrsim2.6\sigma$ levels assuming a global search including
all trials below 0.5 Hz. The fact that the QPO is present in two different detectors at different epochs is ensuring that the signal is detector-independent, albeit it is not statistically significant in the Chandra data alone.

2.4 Stacked Swift/XRT PDS.

The XRT on board Swift has an effective area (49) of $\lesssim 1/20^{th}$ that of XMM-Newton/EPIC’s combined pn+MOS (50). Nevertheless, using 1000-second light curve segments spread across the $\gtrsim 450$ d flare we constructed an average 0.3-1.0 keV PDS. Similar to XMM-Newton extraction, in order to mitigate the pile-up issue but at the same time not compromise on the count rate, we considered only grade 0 events within an 25″ circular region. The QPO at 7.65 mHz is recovered at over the $3\sigma$ (single trial) confidence level. This is shown in Fig. 2B. This again suggests that the QPO was stable over the 450 d after its discovery.

2.5 The 7.65 mHz QPO is stable.

The fact that the 7.65 mHz QPO is present in the average PDS of eight observations scattered over 450 d demonstrates that the QPO is stable throughout the first 450 d of the flare. We constructed a dynamic PDS where we show the progress of the PDS as we add one additional PDS (see Movie S1). This demonstrates that the 7.65 mHz QPO does not originate from a single observation that dominates the average PDS. Instead, the signal gradually improves as more and more data is added. This implies that the signal is present to some extent in all the individual XMM-Newton and Chandra power spectra. Furthermore, the average Swift PDS taken over 450 d also indicates that the QPO has to be stable.

3 QPO’s Coherence, fractional rms amplitude, duty cycle, and folded light curves.

The coherence of the QPO (centroid frequency ($\nu$)/width ($\Delta \nu$)) in the combined XMM-Newton and Chandra power spectrum can be estimated from the unbinned power spectrum obtained by averaging the 8 individual PDS, i.e., before averaging neighboring frequency bins. Modeling the QPO with a Lorentzian functional form results in a best-fitting centroid and width of $7.89\pm0.1$ mHz and $0.5\pm0.2$ mHz, respectively. Combining these two values, the coherence of the QPO is $16\pm6$.

To visualize this modulation in the time domain, we first folded the Chandra (C1) light curve as it is not severely effected by pile-up (see below). We estimated the fold period from the power spectrum of the light curve over-sampled by a factor of 3, i.e., total light curve length is 3 times the original C1 light curve. Oversampling translates to subtracting the mean from the light curve and padding the end with zeros and then computing the power spectrum. Oversampling is a commonly used technique in pulsar period searches (51–53). For folding purposes, we used
the frequency that corresponds to the highest power within 7.65±0.7 mHz, where 0.7 mHz is the upper limit on the QPO’s width (see above). For C1 this period is 134.6±0.1 seconds (or 7.43±0.006 mHz). The uncertainty on the period was estimated using Eq. 3.12 of Chakrabarty (1999) (51) which was derived by Middleditch (1976) (52). The resulting folded light curve is shown in Fig. 3. The fractional modulation amplitude derived from the best-fitting sinusoidal curve is 35±8%, consistent (within the 90% confidence limit) with the measurement from the power spectrum which yields 59±11%.

**Duty Cycle:** The observing time \(T\) to detect a QPO feature at a single trial statistical significance of \(n_{\sigma}\) and the mean source \(S\) and the background count rates \(B\) are related (36) as,

\[
n_{\sigma} = \frac{r^2}{2} \frac{S^2}{S+B} \sqrt{\frac{T}{\Delta \nu}}
\]

where \(r\) and \(\Delta \nu\) are the fractional rms amplitude and the width of the QPO feature, respectively. Assuming that during the Chandra observation, the QPO had a constant rms and width, we can estimate an \(n_{\sigma}\) value and compare it to the observed statistical significance. Using an rms value of 35% and a QPO width of 1 mHz implies an \(n_{\sigma}\) of 2.4\(\sigma\), a number close to the observed 3\(\sigma\) value. This would imply a QPO duty cycle of almost 100%. However, if we assume an rms value of 60% (the upper end of the uncertainty) then the expected \(n_{\sigma}\) is 7\(\sigma\). In this case, the QPO duty cycle is roughly 20% (≈ \((\frac{3}{7})^2\)). Given the large uncertainty in the QPO’s rms amplitude it is difficult to assess the true duty cycle of this QPO.

Chandra observations are typically dithered and as a result the source region does not lie on the same pixels throughout the exposure. The detector has some bad columns/pixels and if the source region dithers in and out of these bad pixels this can alter the true count rate. Because the nominal periods for ACIS in the two dither directions are 1000 and 707 s, it is unlikely to produce any periodic modulation on a timescale of 131 seconds. However, it is plausible that the spacecraft dithering could effect the amplitude of the QPO. To investigate this possibility we used the Chandra ciao tool dither_region to estimate the fractional area of the source region as a function of time during the 25 ks exposure. The source area fraction was unity throughout the observation and therefore we conclude that dithering, and hence bad pixels, had no affect on the rms of the QPO during epoch C1.

We also folded the XMM-Newton observations at their respective fold periods. Similar to C1 above the fold period for each XMM-Newton observation corresponds to the frequency of the highest power bin within 7.65±0.7 mHz in the oversampled PDS. The resulting folded light curves are shown in Fig. S10 and are described in Table S4. The power spectra from individual XMM-Newton observations do not have sufficient signal-to-noise to resolve the QPO and therefore it was not possible to estimate the QPO rms directly from the PDS. Instead, we estimated the fractional rms by fitting a sinusoidal curve to the folded light curves (see Table S4). Except for epoch X5 the rest of the XMM-Newton observations are piled-up, and therefore the rms amplitudes should be treated as the lower limits. However, because of low level of pile-up in X5 we conclude that the ≈3% value is close to the true fractional rms amplitude of
the QPO during at least epoch X5.

The fact that this value is much lower than the rms during C1 suggests that the QPO underwent a strong amplification between X5 and C1 which were separated by a duration of roughly 50 days. The long-term evolution of the QPO’s fractional rms amplitude is shown in Fig. S11.

4 Estimating Chandra/ACIS Pile-up Fraction.

The mean count rate during the Chandra observation (C1 in Fig. 1) was only roughly 0.008 counts/sec. At such low count rates pile-up is expected to be minimal. Nevertheless, we estimated the pile-up fraction using the ciao tool pileup_map. Using the counts/frame in the brightest pixel in the pile-up image generated from this tool we calculated the pile-up fraction to be only \(\approx 4.5\%\) (see Eq. 3 of pile-up analysis guide (54)). Using Portable, Interactive, Multi-Mission Simulator (PIMMS) (55) also gives a similar value. In summary, because the Chandra data were not severely piled-up we could estimate the rms value of the QPO during the C1 epoch in Fig. 1.

Supplementary Text.

5 Ruling out a Pulsar Origin.

A pulsar origin for ASASSN-14li–and thus the QPO–is unlikely for many reasons.

1. The size of ASASSN-14li’s optical/UV photosphere (\(\sim 10^{14}\) cms (15, 16)) is a factor of \(\gtrsim 10^5\) larger than the characteristic emission size of a 2M\(_\odot\) neutron star’s accretion disk of a few thousand gravitational radii. A stellar-mass BH origin can also be ruled out on the same basis.

2. ASASSN-14li’s radio emission is not dominated by emission from a neutron star. Its radio spectral energy distributions are consistent with synchrotron self-absorption with a characteristic emission size of a few\(\times 10^{16}\) cms (11, 22). This is several orders of magnitude larger than a typical neutron star’s size of roughly 10\(^6\) cms.

3. ASASSN-14li’s host galaxy distance of 90.3 Mpcs (3) would imply that the putative neutron star is emitting at an apparent bolometric (x-ray+optical+UV) luminosity \(>3\times 10^6\) its Eddington limit. This is plausible in light of the recent discovery of so-called ultraluminous x-ray (ULX) pulsars (56) with maximum luminosities upto \(7\times 10^{40}\) erg/sec. However, ASASSN-14li would need to be an extreme ULX pulsar with a factor of \(>1400\) brighter than even the most luminous ULX pulsar known (57). All three known ULX pulsars and the bursting pulsar GRO J1744-28 (58) are highly variable (56, 57). They reach super-Eddington luminosities only for brief periods of a few days at a time (56,
57). ASASSN-14li on the other hand has an average apparent bolometric luminosity of $>5 \times 10^{43}$ erg/sec or $\approx 2 \times 10^5$ times Eddington for a neutron star for over at least two years after its discovery (15).

4. ASASSN-14li’s x-ray spectrum is unlike any ULX pulsar. Because all X-ray bright jets show hard x-rays, if ASASSN-14li’s x-ray emission were highly beamed hard x-rays would be present. This is contrary to the observed very soft x-ray spectrum (9, 16).

5. The observed 7.65 mHz feature has a finite width (Fig. 2; coherence=16±6) unlike a pulsar’s signal that is expected to be highly coherent (see above).

6. In principle, ASASSN-14li could be a foreground pulsar that happened to spatially coincide with a background galaxy. This would be highly coincidental especially because there are no known pulsars in this sky region (59). Nevertheless, we estimated the chance coincidence with a background galaxy as:

$$\frac{N_{\text{gals}} \times \pi R^2_{\text{x-ray}}}{\pi R^2_{\text{gal}}}$$  \quad \text{(S1)}

where $N_{\text{gals}}$ is the number of galaxies within a circle of radius $R_{\text{gal}}$ and centered on ASASSN-14li. $R_{\text{x-ray}}$ is the typical positional uncertainty of Chandra/ACIS which has been estimated to be 0.8″ (90% positional accuracy (60)). Using the galaxy catalog from the Sloan Digital Sky Survey (data release 14 (61)) we find $N_{\text{gals}}=1505$ within a circular area of radius 10′. This translates to a chance coincidence of less than 3%. The mean and the lowest $g$-band magnitude of galaxies around ASASSN-14li is 22.9 and 28.4, respectively while ASASSN-14li’s host galaxy–prior to the TDE–had a $g$-band magnitude of 16.1 (3). We repeated this estimate with a sky area of $\pi 5′ \times 5′$ and $\pi 15′ \times 15′$ to find that the resulting chance probabilities are the same. We stress that the above 3% estimate can be considered conservative (upper limit) as it includes chance coincidence with any part of the galaxy not just the center.

7. ASASSN-14li’s multiwavelength properties are unlike any neutron star outburst and are similar to many previously known TDEs. A pulsar origin would only then compel us to conclude that all previously-known TDEs are foreground x-ray pulsars that perfectly coincided with background galaxies, which is unlikely.

6 The Five Frequencies of Motion around a Black Hole.

A test particle moving in the strong gravity of a black hole has three fundamental frequencies. The fastest at any given radius is the Keplerian orbital frequency ($\nu_\phi$) for motion in the equatorial plane. Perturbations can induce two additional frequencies in the radial and the vertical directions. These are known as the radial ($\nu_r$) and the vertical epicyclic ($\nu_\theta$) frequencies,
respectively. Beating between these three coordinate frequencies can lead to two additional frequencies: \( \nu_{LT} = \nu_\phi - \nu_\theta \) and \( \nu_{per} = \nu_\phi - \nu_r \), known as the Lense-Thirring precession and the periastron precession frequencies, respectively. The frequencies are defined as follows:

\[
\nu_\phi = \pm \frac{c^3}{2\pi GM} \left[ \frac{1}{r^{3/2} \pm a} \right] \tag{S2}
\]

where \( r \) is the radius in units of gravitational radius, \( R_g = GM/c^2 \). \( G, M, \) and \( c \) are the gravitational constant, black hole mass, and the speed of light, respectively. \( a \) is the black hole’s dimensionless spin parameter defined as \( a = J/(GM/c^2) \). \( J \) is the black hole’s angular momentum.

\[
\nu_\theta = \nu_\phi \left[ 1 \pm \frac{4a}{r^{3/2}} + \frac{3a^2}{r^2} \right]^{1/2} \tag{S3}
\]

\[
\nu_r = \nu_\phi \left[ 1 - \frac{6}{r} \pm \frac{8a}{r^{3/2}} - \frac{3a^2}{r^2} \right]^{1/2} \tag{S4}
\]

The upper and lower signs in the above equations refer to the prograde and retrograde orbits, respectively \((18, 19)\). The equations are exact results for the Kerr geodesics \((62)\).

7 Potential QPO Mechanisms.

Because a star can approach the disrupting BH from any direction, its orbital plane is expected to be arbitrarily oriented with respect to the BH’s spin axis. The transient accretion disk that forms after disruption is thus expected to be born largely misaligned with respect to the BHs spin axis, in contrast to most accreting BHs (which, as long-lived systems, are expected to exhibit spin-orbit alignment). Past work predicted \((63, 64)\) that the aspherical spacetime around a spinning BH should force such a misaligned disk to precess as a roughly rigid body and produce quasi-periodic modulation of the soft x-ray flux, as is seen in many general relativistic magnetohydrodynamic (GRMHD) simulations of tilted thick disks \((65, 66)\). Assuming the observed 7.65 mHz QPO originates from the global precession of a newly-formed accretion disk would imply, however, that the precessing disk/ring is very narrow. Using the semi-analytical approach for a precessing TDE disk as formulated in \((64)\), for a BH mass between \(10^4\) and \(10^7\ M_\odot\), the implied radial extent of the disk must be between a few tens of gravitational radii to a fraction of a gravitational radius, respectively, even for maximally spinning BHs. Even narrower disks are required for smaller spin values.

To produce such narrow disks, the star would need to plunge deep into the gravitational potential of the BH. The likelihood of this can be quantified with the penetration parameter, \( \beta \), \((67)\), defined as the ratio of the tidal radius (the radius at which the BH’s tidal forces exceed the star’s internal pressure) and the pericenter radius (distance of the star’s closest approach). For ASASSN-14li, if global disk precession is the origin of the QPO, the penetration parameter
would have to be very high. Assuming a $10^6 M_\odot$ BH, $\beta$ has to be $\approx 25-50$ to tune the pericenter (and initial disk outer edge) to the ISCO scale for a rapidly spinning Kerr BH.

As the dynamical fraction of TDEs with penetration parameters $>\beta$ is at most $\approx 1/\beta$ (68), it requires fine-tuning to produce narrow accretion tori for BHs in the mass range inferred for ASASSN-14li. The details of the disk formation process in TDEs are complicated and subject to theoretical debate (69, 70), although for very relativistic pericenter velocities disk formation may proceed more efficiently (71). Even if a narrow, efficiently circularized TDE disk is produced for a high-$\beta$ disruption, such a disk would likely expand outward in a quasi-viscous way, although perhaps shocks from returning debris streams could regulate this expansion. In summary, a global disk precession origin for this QPO is disfavored by the need for extensive fine-tuning and the observed long-term stability.

Alternatively, GRMHD simulations of tilted accretion flows have shown high variability from their innermost annuli due to “plunging streams” that transport matter from the disk into the BH horizon. While this variability can occur in the frequency range presented by ASASSN-14li (72), it exhibits neither the observed large amplitudes nor the long-term stability (73), and therefore does not appear to be a promising model for the ASASSN-14li QPO.

Theoretical work (74, 75) has predicted the occurrence of long-lived, discrete, narrow and nodally precessing rings in the inner regions of a misaligned accretion flows, although the viability of such “disk tearing” is still controversial, and has yet to be seen in fully 3-dimensional GRMHD simulations (76). It is also unclear why QPOs from these rings would exhibit such stability over long periods of time, as the global properties of the large-scale TDE disk change dramatically.

A qualitative difference between TDE and standard accretion disks is the generic expectation of spin-orbit misalignment. This suggests that the existence of a high amplitude and stable X-ray QPO in ASASSN-14li may originate in a variability mechanism unique to tilted disks, but none of the three proposed sources of tilted disk variability examined here seem fully satisfactory, posing a challenge for theories of TDE disks, and perhaps tilted accretion systems more generally.

Given the shortcomings of QPO mechanisms related to spin-orbit misalignment, we also consider orbiting hot spots (e.g., (77)) as an origin for the QPO. The hot spot model suffers from the following problems:

1. Over-dense clumps, which might be the source of the hot spots tend to shear out on roughly the local orbital timescale due to differential rotation within the disk. Thence, it seems unlikely they would result in the fairly high coherence observed here, unless the duty cycle was quite high.

2. Assuming hot spots shear out and reform, the narrow range of frequencies seen in this QPO means the hot spots would necessarily always have to form at the same radius, which seems contrived for an isolated disk. In a TDE disk, however, returning debris streams will shock the disk and create hot spots at their point of contact, which is fixed to be the pericenter radius of the original star. However, resulting hot spots would orbit the
black hole too slowly to match the observed QPO frequency, unless the pericenter was quite close to the ISCO (see above). Otherwise, we expect the asymmetry imposed by the gas supply to wash out as the gas flow circularizes into a disk (analogous to accretion in low-mass x-ray binaries).

3. There are instabilities that can produce quasi-stable over-dense clumps in disks (an example is the Papaloizou-Pringle instability (78)). However, those “clumps” are manifestations of wave patterns in the flow. Therefore, they move at the pattern speed (78), which is generally slower than the orbital speed (79), exacerbating the problem of matching the very high frequency of this QPO.

A final possibility is that the QPO is associated with the orbital motion of an intact stellar mass object (a star, stellar core, or compact remnant). This would produce a very coherent QPO signal over very long periods. However, this model suffers from the same problem as the LT precession—the resulting QPO frequency would be too low to explain the observed 7.65 mHz signal, unless the black hole were spinning at close to its maximum value and the perturber were orbiting near the ISCO. It is unlikely that a stellar mass object could be deposited onto a circular orbit by the events leading to the observed TDE—even if a stellar core survived a partial disruption, it would not be energetically capable of tidally circularizing. A hypothetical binary companion to the disrupted star would likely have been ejected by the Hills mechanism (80). If a stellar mass object exists on an orbit between the ISCO and the tidal radius, it must predate the tidal disruption that triggered ASASSN-14li. The short gravitational wave inspiral time within a few gravitational radii of the ISCO (≈ 0.4-20 yr, for orbital frequencies \( \Omega = 7.65 \) mHz, black hole masses of \( 10^6-7 M_\odot \) and companions between \( 1 - 10 M_\odot \)) makes it unlikely that a compact object would be in residence there, and a main sequence star could not survive the local tidal shear. The residence times at the tidal radius are roughly \( \sim 10^4 \) times longer, and mass transfer due to Roche lobe overflow (RLOF) can stabilize main sequence stars in such orbits for up to \( \sim 10^7 \) yr (81, 82), but the orbital frequency there is \( \sim 0.1 \) mHz, far less than the observed QPO frequency. A white dwarf star undergoing RLOF may be the most promising version of this scenario, as its small mass would, for a fixed orbital frequency and black hole mass, produce longer gravitational wave residence times. For a very low-mass white dwarf, with \( M_{WD} = 0.1 M_\odot \), the gravitational wave inspiral time would be \( \approx 190 \) yr if it were in an \( \Omega = 7.65 \) mHz orbit around a \( 10^6 M_\odot \) black hole. Although this inspiral time is longer than that for other possible perturbers, it still implies a high rate of white dwarf inspirals into supermassive black holes based on TDF rates (2).

A final difficulty in explaining this QPO is its increasing amplitude. Of the various QPO models proposed, only the orbiting compact object seems to present a reasonable explanation: If the TDE disk and compact orbiter are initially in different orbital planes, then as they slowly settle into the same plane, their interactions, and hence the QPO, would strengthen over time. For the other QPO models – Lense-Thirring precession and orbiting hot spots – the increasing rms would require that the coherence of the oscillator somehow increases with time. Since effective viscosity is likely to produce dynamical spreading and shearing, it seems more likely
that the coherence would decrease, rather than increase, for these models.
Figure S1: An *XMM-Newton* EPIC (pn+MOS) 0.3-1.0 keV image of the field of view containing ASASSN-14li. The source extraction region is indicated by a dashed cyan circle while the background extraction regions are shown as green circles. The north and east arrows are each 40'' long. This image shows the data set corresponding to obsID 0722480201.
Figure S2: **ASASSN-14li’s source and background light curves using XMM-Newton data sets.** (a), (c), (e): Source + background (black) and background (red) X-ray (0.3-1.0 keV) light curves binned at a resolution of 25 s. The background light curves (red) are normalized to the source extraction area, i.e., divided by a factor of the ratio of the background to source area (=4.7). The green and the magenta vertical lines mark the beginning and the end of all GTIs greater than 10 s. The first 10 ks (or integer multiple of 10 ks segments) of all GTIs greater than 10 ks are highlighted by a shaded blue rectangle. These are the data segments used for constructing the average PDS in Fig. 2. The exact values of the GTIs used for constructing the average PDS are listed in Table. S1. (b), (d), (f): Zoom-in on the background light curves. They were extracted from a total area of 4.7 times the source extraction area.
Figure S3: Same as Fig. S2 showing the data from other observations.
Figure S4: **epatplot outputs showing photon pile-up in XMM-Newton observations of ASASSN-14li.** In each panel the histogram show the observed distribution of the single (s; red), double (d; blue), triple (t; green) and quadruple (q; brown) pixel events. The solid curves are the expected distributions. The expected distributions, especially for the single and double events, do not agree well with the observed data. This mismatch is an indication of photon pile-up, evident in all the observations with X5 ((e)) being least affected (see sec. 1 for more discussion).
Figure S5: **Chandra/ACIS x-ray image of ASASSN-14li.** Only one source is visible, ASASSN-14li, with no evidence for source contamination. *Chandra* and *XMM-Newton* extraction regions are shown as white (2.5″) and green (40″) circles, respectively.
Figure S6: **Probability plot to assess ASASSN-14li’s power spectral noise powers against white noise ($\chi^2$ distribution).** If the data points lie on straight line, then it suggests (at least qualitatively) that the data are consistent with the hypothesized model which in our case is a $\chi^2$ distribution with 128 degrees of freedom scaled by a factor of 1/64 (see text for details).
Figure S7: Tests for white noise in the PDS for ASASSN-14li. (a) The empirical distribution function (EDF) of ASASSN-14li’s noise powers in 0.001-0.1 Hz, i.e., surrounding the QPO signal at 7.65 mHz. The blue histogram is the data while the red curve is the expected \( \chi^2 \) distribution for white noise. The EDF tracks the expected CDF over the range of observed power values. The dashed orange line marks the power value of the highest bin in the QPO. (b) The probability density function of the observed noise powers compared with the expected \( \chi^2 \) distribution for white noise. (c) Distribution of the K-S test statistic for a sample size of 122 (the number of bins between 0.001 and 0.1 Hz minus the three QPO bins) for a \( \chi^2 \) distribution. The observed test statistic value (dashed red line) lies close to the median of the distribution (magenta line) and is thus consistent with ASASSN-14li’s noise powers being white (see sec. 2.1.3). (d) Distribution of Anderson-Darling test statistic for a sample size of 122 for a \( \chi^2 \) distribution. Again, it is evident that ASASSN-14li’s noise powers are consistent with the expected \( \chi^2 \) distribution.
Figure S8: **Global statistical significance under red noise** (a) Results from Monte Carlo simulations showing the global probability to exceed (statistical significance) the maximum normalized power below 0.5 Hz ($\xi_{\text{max}}$) under the assumption that the red noise has a powerlaw index of -0.3 and a normalization of 0.038. The specific value of 0.038 is the 1σ upper limit on the best-fitting normalization for a fixed index of -0.3. Therefore, the statistical significance should be considered conservative, i.e., a lower limit (see sec. 2.2). The normalized power value in the highest observed QPO bin is indicated by the dashed red line. (b), (c), (d), (e) Same as (a) but for a red noise index of -0.7, -1.0, -1.4, and -1.7, respectively. The normalization values are 1σ upper limits estimated directly from modeling ASASSN-14li’s unbinned PDS (see sec. 2.1.2).
Figure S9: *XMM-Newton* and *Chandra* power spectra of ASASSN-14li. (a) Same as Fig. 2A. (b) ASASSN-14li’s x-ray (0.4-1.0 keV) power density spectrum using twelve 2,000 s light curves taken with *Chandra*’s ACIS instrument. The frequency resolution is 1 mHz. The strongest feature again lies at $7.75 \pm 0.5$ mHz and is consistent with the most prominent feature in the average *XMM-Newton* spectrum (see (a)).
Figure S10: **Folded XMM-Newton light curves.** Same as Fig. 3. In each case, the fold period corresponds to the frequency of the highest power spectral peak between $7.65 \pm 0.7$ mHz in the PDS of the longest GTI oversampled by a factor of 3 (see Table. S4). Except for 0770980101 (e) the XMM-Newton datasets suffered from pile-up. Therefore, their respective fractional rms amplitudes should be considered lower limits.
Figure S11: **Amplitude of the QPO in each observation.** X1, X2, X3 and X4 data were piled-up and hence their rms amplitudes are shown as lower limits. A sharp rise in the rms between X5 and C1 is evident (see Table S4).
Table S1: A summary of *XMM-Newton* and *Chandra* observations (C1) used in this paper.
†The number of uninterrupted 10 ks segments.

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Exposure (ks)</th>
<th>Date observed</th>
<th>$N_{\text{seg}}$</th>
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<td>23</td>
<td>2014-12-06</td>
<td>1</td>
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<tr>
<td>X2 0722480201</td>
<td>95</td>
<td>2014-12-08</td>
<td>1</td>
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<tr>
<td>X3 0694651401</td>
<td>25</td>
<td>2015-01-01</td>
<td>2</td>
</tr>
<tr>
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</tr>
<tr>
<td>X5 0770980101</td>
<td>96.5</td>
<td>2015-12-10</td>
<td>2</td>
</tr>
<tr>
<td>C1 18345</td>
<td>25</td>
<td>2016-01-28</td>
<td>2</td>
</tr>
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</table>
Table S2: **Good time intervals used for the PDS.** These resulted from the criterion of selecting only data segments that were uninterrupted for over 10 ks (see Figs. S2 and S3). †The start and stop times of the GTIs used in extracting the average PDS shown in Fig. 2. These are measured in seconds since 1997-12-31T23:58:56.816 Coordinated Universal Time (UTC), i.e., MJD of 50814.0, for both *XMM-Newton* and *Chandra* data. They have been rounded off to the nearest second.

<table>
<thead>
<tr>
<th>ObsID</th>
<th>start time (s)†</th>
<th>end time (s)†</th>
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<tr>
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<tr>
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Table S3: **Constraints on the red noise strength and QPO’s highest bin’s statistical significance.** †The normalization was obtained by directly fitting ASASSN-14li’s unbinned PDS with a model consisting of a powerlaw + constant + QPO (see sec. 2.2). For the purposes of simulating the red noise curve and thus estimating the red-noise significance values, we used the upper limit on the normalization, i.e., best-fit normalization + 1σ uncertainty. *Global significance of the QPO’s highest bin in red noise power spectra simulated using the Monte Carlo methodology described in sec. 2.2 (also see Fig. S8). ††This is limited not by the strength of the QPO but by the number of simulations we could perform (see Fig. S8).

<table>
<thead>
<tr>
<th>Red-noise slope</th>
<th>Normalization†</th>
<th>Significance*</th>
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<tr>
<td>-0.3</td>
<td>(1.9±1.9)×10^{-2}</td>
<td>≈3.9σ</td>
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<tr>
<td>-0.7</td>
<td>(1.8±0.9)×10^{-3}</td>
<td>&gt;4.1σ††</td>
</tr>
<tr>
<td>-1.0</td>
<td>(1.8±0.7)×10^{-4}</td>
<td>&gt;4.1σ††</td>
</tr>
<tr>
<td>-1.4</td>
<td>(5.1±2.2)×10^{-6}</td>
<td>&gt;4.1σ††</td>
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<tr>
<td>-1.7</td>
<td>(3.1±1.4)×10^{-7}</td>
<td>&gt;4.1σ††</td>
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Table S4: **Properties of the QPO at various epochs.** *Modified Julian Date. †The fractional rms amplitude of the QPO estimated from fitting a sinusoidal curve to the folded light curves (units of % of mean count rate). ††Fold periods (in seconds) correspond to the frequency of the power spectral bin with the highest power within 7.65±0.7 mHz in the oversampled PDS (see sec. 3).*

<table>
<thead>
<tr>
<th>ObsID</th>
<th>MJD*</th>
<th>rms†</th>
<th>Fold-Period††</th>
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<tbody>
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<td>&gt;1.4±0.3</td>
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<tr>
<td>X3</td>
<td>0694651401</td>
<td>57024.02</td>
<td>&gt;1.1±0.3</td>
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<tr>
<td>X4</td>
<td>0694651501</td>
<td>57213.40</td>
<td>&gt;3.3±0.8</td>
</tr>
<tr>
<td>X5</td>
<td>0770980101</td>
<td>57367.28</td>
<td>2.8±0.7</td>
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<tr>
<td>C1</td>
<td>18345</td>
<td>57415.737</td>
<td>35±8</td>
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**Movie S1:** The movie shows gradual improvement in the QPO signal at 7.65 mHz as more data is added. This suggests that the QPO is long-lived and present in all of the observations.