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Probing the Strong (Stationary) Gravitational Field of Accreting Black Holes with X-ray Observations

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Abstract
High throughput time-resolved observations of accreting collapsed objects at X-ray energies provide key information on the motions of matter orbiting a few gravitational radii away from black holes. Predictions of general relativity in the strong field regime, such as relativistic epicyclic motions, precession, light bending and the presence and radius of an innermost stable circular orbit in the close vicinity of a black hole can be verified by making use of two powerful diagnostics, namely relativistically broadened Fe-Kα lines and variability on dynamical timescales, quasi periodic oscillations in particular. Moreover tomography and reverberation techniques relying upon combined spectral timing and polarimetric timing provide an entirely new perspective in the field. Both the low and high spacetime curvature regimes of gravity can be probed by studying black holes of vastly different masses in X-ray binaries and Active Galactic Nuclei, opening up the possibility of testing also some alternative theories of gravity. To achieve these goals, very large area X-ray instrumentation with good spectral resolution and polarimetric capability is required. Prospects and projects in this area of research are briefly surveyed.

Keywords Tests of relativistic gravity · Black holes · Accretion disks · X-ray astronomy · Theories of gravity

1 Introduction

Gravity has been tested extensively in the weak-field regime through measurements of phenomena occurring at distances many orders of magnitude larger than the gravitational radius, $R_g = GM/c^2$, (i.e. 1.5 km for 1 solar mass, $M_\odot$), where relativistic effects are small and often represent only little perturbations to the Newtonian values.

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For instance binary pulsar systems hosting two neutron stars (NSs), the so-called relativistic binary pulsars, have provided among the most important and accurate tests of general relativity (GR) [25,36]. In fact their pulses represent extremely accurate clock ticks through which the orbital motion and spacetime characteristics can be measured, but only over sizes comparable to the separation of the two stars, i.e. $\gg 10^4 R_g$. Comparatively little is known about the strong-field regime of gravity. Owing to their extreme compactness, black holes (BHs) of all masses and, to a lesser extent, NSs provide the best environment to investigate strong-field gravity by studying the motion of matter and light very close the them. The measurement of strong-field effects of GR in the highly *dynamical spacetimes* of merging BH and NS binaries are among the most remarkable results obtained through the recent detections of gravitational wave signals by the LIGO and Virgo interferometers [1]. However, in the *stationary spacetimes* of (non-merging) compact objects there are important strong-field GR effects taking place at radii of $< 10\ R_g$ that have not yet been accurately measured or even detected: these include e.g. epicyclic motions, frame-dragging, light bending, polarization effects and the properties of the innermost stable circular orbit (ISCO).

Accretion flows in these systems involve amounts of mass and self-gravity that are negligibly small relative to the mass and gravitational field of the compact object. For instance accretion disks around NSs and stellar mass BHs have a factor of $\sim 10^{-8} - 10^{-9}$ smaller masses than that of the compact object (see e.g. [43]). Therefore, unlike merging binaries and other systems that can be studied by their gravitational wave emission, NSs and BHs that undergo accretion are characterised by a *stationary* spacetime probed by a *test fluid*—the accreting matter—that does not perturb the metric. Because of the very small size of compact objects, accretion toward them is mediated by a disk if matter is endowed with even a modest amount of angular momentum. Disk matter releases a sizable fraction of its rest-mass energy in the form of powerful high-energy radiation (mainly X-rays) from deep in the gravitational potential well of these objects, as it gradually spirals-in as a result of viscous coupling at different radii in the disk. Most of the power is generated in the innermost region, where motions take place at a sizable fraction of the speed of light and are affected by strong-field gravity effects. Therefore X-ray emission from accreting BHs holds the potential to verify some key predictions of GR in the strong field regime; two diagnostics have been studied over the last two decades which are especially promising in this respect:

– The extremely broad and redshifted profile of the Fe-Kα emission line around ~ 6.4 keV that is produced by the combination of relativistic effects arising from the motion of disk matter in the vicinity of compact objects (Fig. 2) [9,42]. Such profile is observed in supermassive BHs of Active Galactic Nuclei (AGNs) [5], as well as in stellar mass BHs and NSs. It is determined by relativistic beaming, time dilation, red/blue-shifts, light bending and frame dragging of matter orbiting the innermost regions of accretion disks with speed $> 0.1\ c$; therefore information on a variety of effects predicted by strong field GR is encoded in the profile (that is besides the emissivity and geometry of disks extending down to the ISCO). Observations with past and current generation X-ray astronomy facilities, yielded estimates of BH spin, some of which approach the maximum rotation allowed in the Kerr metric [34] (Fig. 1).

– Very fast X-ray flux variability generated by matter accretion into BHs and NSs provides another powerful diagnostic of geodetic motion in the strong field regime. As early as 1972 Sunyaev discussed the possibility to identify black holes and discriminate between the cases where a Schwarzschild or Kerr metric prevails, based on the fastest signals arising from a disk at the ISCO radius [41]. Fruition of this diagnostic began only when fast Quasi Periodic Oscillations (QPOs) with frequencies close to those expected from bound orbits at radii $< 10\ R_g$ were discovered in the power spectra of the X-ray light curves from a number of accreting NSs and several stellar mass BHs. Different QPOs excited at the same time were studied in a number of cases, whose variable frequency extended up to ~ 450 and ~ 1.3 kHz in the highest mode of NSs and BHs, respectively (Fig. 2) (see [45] for a review). QPOs have been detected also from a few supermassive BHs (see e.g. [13]). Models of the complex QPO phenomenology are based on hydrodynamical flows which involve combinations of the fundamental frequencies of motion of matter in the strong field regime, i.e. one azimuthal and two (radial and vertical) epicyclic frequencies. The regime that applies is such that these frequencies differ substantially from their Newtonian equivalent (see [4] for a review). For example, the radial epicyclic frequency is zero at the ISCO, reaches a broad maximum at a ~ 1.4 times larger radius and then decreases as $r^{-3/2}$; such behavior is characteristic of strong gravitational fields close to collapsed objects and is not present in weak field approximations of GR (Fig. 3). QPOs thus hold a great diagnostic potential for measuring strong field gravity effects, such as, for instance, the nulling of the radial epicyclic frequency at the ISCO, precessional motions induced by frame dragging and strong field light bending.

The potential of these two diagnostics has been exploited only to a modest extent owing to the relatively small signal to noise ratio (S/N) and/or energy range and resolution afforded by past and present generation instrumentation for X-ray astronomy. For instance QPO signals have been studied almost exclusively by resorting to statistical averages (of power spectra, mainly) thousands to billion times longer than the QPO periods. Similarly the detection and study of relativistically broadened Fe-line profiles has required long exposure times (many hours to days typically), while systematic uncertainties originating from subtraction of underlying X-ray emission and narrow spectral features have persisted, due to limitations in spectral range and resolution.[1] It is only in recent years that combined spectral-timing X-ray studies based on reverberation and tomography analysis techniques have been attempted; despite poor S/N very promising results have been obtained (see [8] for a review).

Major progress in this area of research is expected from the development of advanced instrumentation for X-ray astronomy satellites of greatly improved area, energy range and resolution which can exploit the timing, spectral and combined spectral/timing diagnostics by studying fast variations within the *dynamical* timescale in which they occur. The addition of an X-ray polarimeter, as planned for the eXTP

[1] Note that QPOs and relativistic Fe-lines are being studied also with the recently launched missions ASTROSAT [31] and NICER [33].

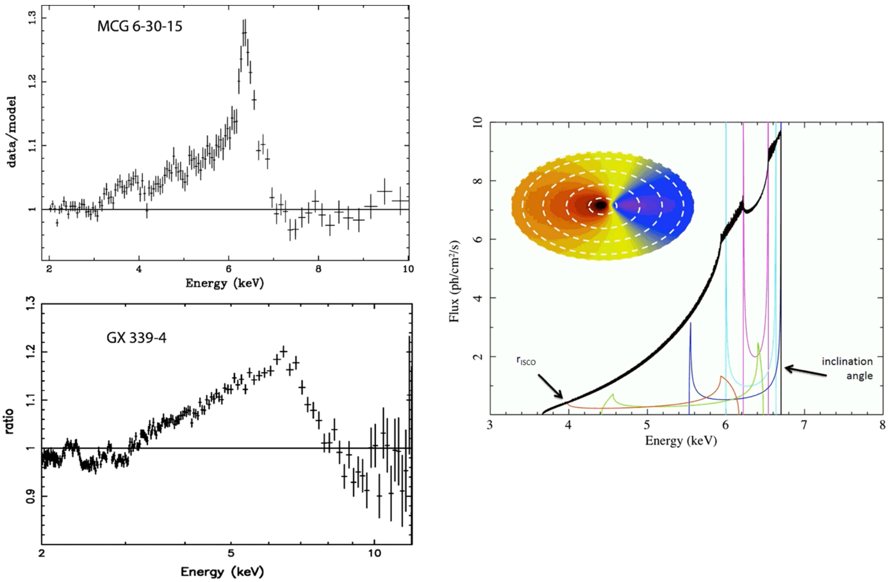


Fig. 1 Examples of relativistics Fe-Kα line profiles from an accretion disk around a supermassive black hole (top left panel) and a stellar mass black hole (bottom left panel), as determined with present generation instrumentation (the X-ray CCDs on board XMM/Newton; note that pileup effects reduce drastically the S/N of bright X-ray sources, including stellar mass BHs; exposure times are in the $\sim$ 50 ks range) [10,29,42]. The right panel shows the profile expected from the inner regions of a disk surrounding a non-rotating BH (black line); the colored lines show the contributions to the line profile from annuli at different radii in the disk (from left to right 6, 10, 30, 100, 400 R_g, courtesy Brenneman); the lowest energy end of the profile is a proxy of the innermost disk radius (R_{ISCO} in this plot), the blue peak is sensitive to the disk inclination. The inset shows a color-coded map of the relativistic Doppler and gravitational shifts in the disk; redshift dominates at the smallest radii

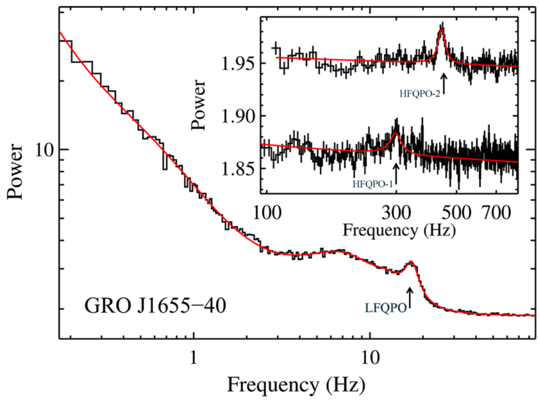


Fig. 2 QPOs from a stellar mass accreting black hole as revealed by the RXTE/PCA. The broad peaks in the power spectrum of the X-ray light curves correspond to the low frequency QPOs ($\sim$ 15 Hz) and the two high frequency QPO ($\sim$ 300 and $\sim$ 450 Hz). This is the only triplet of simultaneous QPOs that has so far been observed from an accreting BH ([30] and references therein). Based on this triplet BH mass and spin were estimated through the application of the RPM

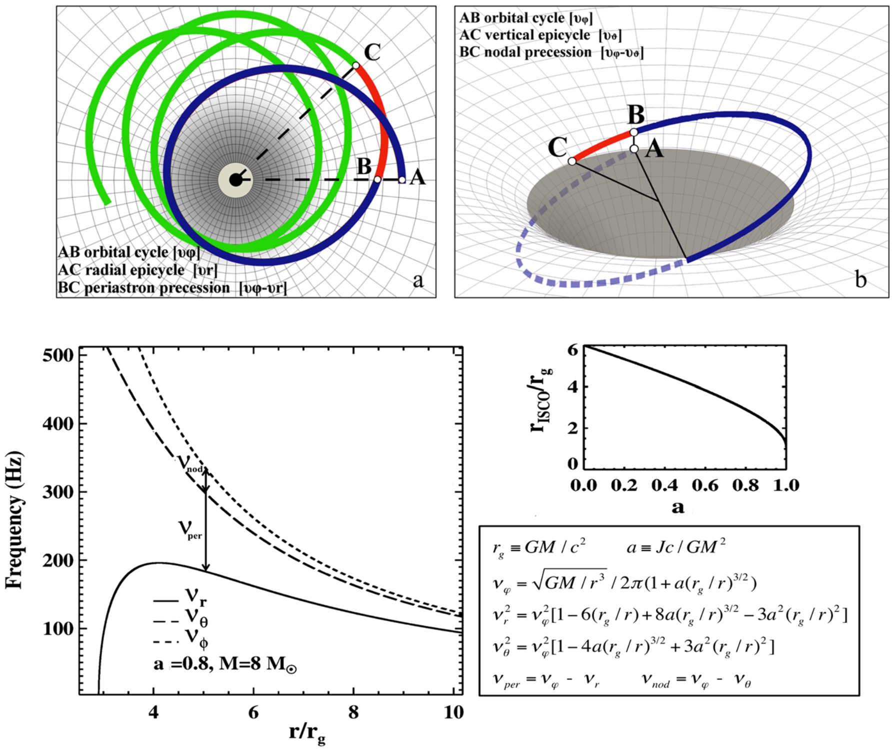


Fig. 3 Example of an eccentric, non-equatorial orbit in the Kerr metric, as seen face on (top left panel), and from a $\sim 60°$ inclination angle (top right panel). Cycles are represented for each of the three different fundamental frequencies of motion: azimuthal, radial epicyclic and vertical epicyclic. Periastron and nodal precessional motions are shown (embedding diagrams are plotted to help visualisation). Bottom left panel: Fundamental frequencies of motion for an infinitesimally eccentric and tilted orbit around a Kerr black hole with $M = 8$ $M_\odot$ and spin parameter $a = 0.8$ as a function of radius. Unlike ν_ϕ and ν_θ, the radial epicyclic frequency ν_r decreases with radius close to the compact object, reaching zero at the ISCO radius. The double arrowed segments show the periastron and nodal precession frequencies at a radius of 5 R_g. Middle right panel: ISCO radius as a function of a for corotating orbits. Bottom right panel: formulae for the fundamental frequencies in the Kerr metric

mission (see Sect. 2), will provide an additional diagnostics of GR effects in the strong field regime.

2 X-ray Instrumentation

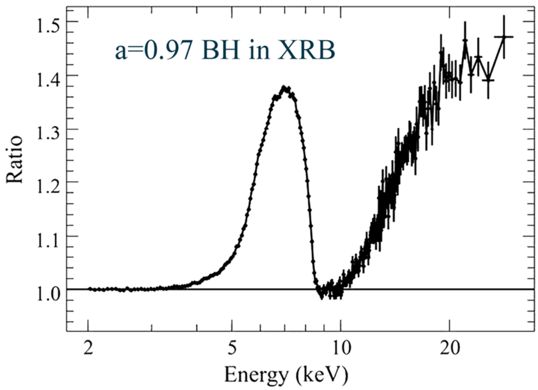
Large area X-ray astronomical instruments are developed by either increasing the physical size of non-imaging detectors that are placed behind a collimator, or by increasing the collecting surfaces and/or multiplicity of telescopes or concentrators, coupled to (small) focal plane detectors. Both approaches are being followed in the study of programs for future missions, the former in the medium-energy X-ray range ($\sim 2 - 50$ keV) and the latter in a softer range ($\sim 0.1 - 10$ keV). The largest area instruments greatly benefit from the adoption of silicon drift detectors (SDDs) which provide an order of magnitude improvement in weight, power consumption and cost per unit area over proportional counters, have good spectral resolution and do not suffer from pileup and deadtime effects [12]. We briefly summarise here the characteristics of satellite programs for the mid 2020s that have been extensively studied and provide the best prospect to investigate the strong-field regime of gravity through X-ray diagnostics.

- The *Large Observatory For x-ray Timing* (LOFT) is a medium-size mission which has been proposed and studied within the ESA Cosmic Vision program [11]. Its main instrument, the Large Area Detector (LAD) affords an effective area of $\sim 8-10$ m^2 (more than one order of magnitude larger than X-ray instruments of the past and present generations) in the $\sim 2-80$ keV range; it exploits large monolithic SDDs with a spectral resolution of $\sim$ 200 eV over the entire band. Being an non-imaging instrument, its field of view is limited to ~ 1 deg^2 by lead-glass collimators using micro-channel plate technology and overlaid on top of the SDDs. A *Wide Field Monitor* (WFM) based on position-sensitive SDDs detectors and coded-mask imaging is designed to constantly look at about 1/4 of the X-ray sky in the $2-50$ keV range at any one time, identifying suitable source states and transient events to be followed up in pointed observations with the LAD.
- The *enhanced X-ray Timing and Polarimetry Mission* (eXTP) is a Chinese mission with extensive international participation, being studied for a perspective launch in the mid-20's [48]. The payload consists of: (i) a smaller version of the LOFT LAD with an effective area of $\sim 3-4$ m^2; (ii) a set of 9 X-ray optics (the Spectroscopic Focusing Array SFA) operating in the $\sim 0.5-20$ keV band with total effective area of $\sim$ 0.7 m^2 and SDDs in the focal plane; (iii) the Polarimetry Focusing Array (PFA), a set of four X-ray telescopes with imaging gas photo-electric polarimeters and total effective area of $\sim$ 500 cm^2; (iv) a Wide Field Monitor (WFM) similar to the LOFT/WFM, but with $\sim$ 30% smaller field of view. The suite of eXTP instruments will allow the simultaneous exploitation of spectral-timing-polarimetry diagnostics for the first time.
- The *Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays* (STROBE-X) is one of NASAs Astrophysics Probes Mission Concept Studies [47]. It comprises three instruments: (i) the X-ray Concentrator Array (XRCA) covers the soft band ($0.2-12$ keV) with an array of lightweight optics and small solid state detectors with CCD-like ($\sim$ 100 eV) energy resolution, attaining an effective area of $\sim$ 3 m^2; (ii) the harder band is covered by a $\sim$ 10 m^2 LAD with similar characteristics to those of the LOFT/LAD; (iii) a sensitive *Wide Field Monitor* (WFM) similar to LOFT's.

3 Exploiting the Fe-line and QPO Diagnostics

Figure 4 gives an impression of the kind of S/N increase in the measurement of relativistic Fe-line profiles that will be attained with a $\sim$ 8 m^2 LAD-type detector from an accreting stellar mass BH in an X-ray binary (compare with the bottom left

Fig. 4 Simulations of the Fe-line and Compton hump from a relativistic accretion disk that would be observed with an ~ 8 m^2 LAD-type detector in a 1 ks exposure of a 1 Crab stellar mass fast spinning BH in an X-ray binary. BH spin and disk inclinations can be measured to $\sim 1\%$ accuracy



panel of Fig. 1). These Fe-Kα lines originate in the *reflection* of continuum X-ray radiation by the relativistic accretion disk (Fig. 5). Features arising from *reflection* are present also in the observed spectra at energies above and below those of the Fe-line, making modeling of the overall spectrum complex. Key information on the innermost disk regions, those closest to the ISCO, where strong filed effect are most pronounced, is encoded in the extreme red wing of the Fe-line profile (see right panel of Fig. 1). The S/N of LAD-type instruments allows extraction of highly accurate relativistic Fe-line profiles, translating among other things into precise ISCO radius and spin measurements of accreting BHs.

GR predicts that orbital, and radial and vertical epicyclic frequencies of matter motion depend on orbital radius in a very distinctive way. Multiple, simultaneous QPOs in the X-ray flux of NS systems whose frequency varies in some cases in a correlated fashion have been used to construct models in which different QPOs can take place at the same time and whose frequency is related to the fundamental frequencies of motion (see [4] for a review). The relative simplicity of the spacetime around BHs (where matter motions are not affected by complications such as the presence of a magnetosphere or the internal mass distribution; that is unlike the case of NSs) makes BH QPO-based measurements of strong field effects especially conclusive. However BH QPOs, the highest frequency modes in particular, are considerably rarer and weaker than those of NSs. Long, high S/N observations such as those that can be carried out with LAD-type detectors are thus essential.

Figure 6 shows the evolution of the QPO frequencies that would be produced by an orbiting shear-elongated luminous region in full (Kerr) GR in response to changes in the orbiting radius. The simulation is based on the properties of the only triplet of simultaneous QPO—a pair of high frequency QPOs and a low frequency QPO—detected so far from a BH binary (see Fig. 2) [30]. The relativistic signals (including some harmonics and combinations of them) and their characteristic frequency-dependence on radius as predicted by the relativistic precession model (RPM) [38–40] would be clearly detected with an ~ 8 m^2 LAD detector (see captions for details). Among other things, the relation of the QPO frequencies verifies the strong field GR behaviour of the radial epicyclic motion to high precision and measures BH mass and spin with $< 0.1\%$ statistical uncertainty.

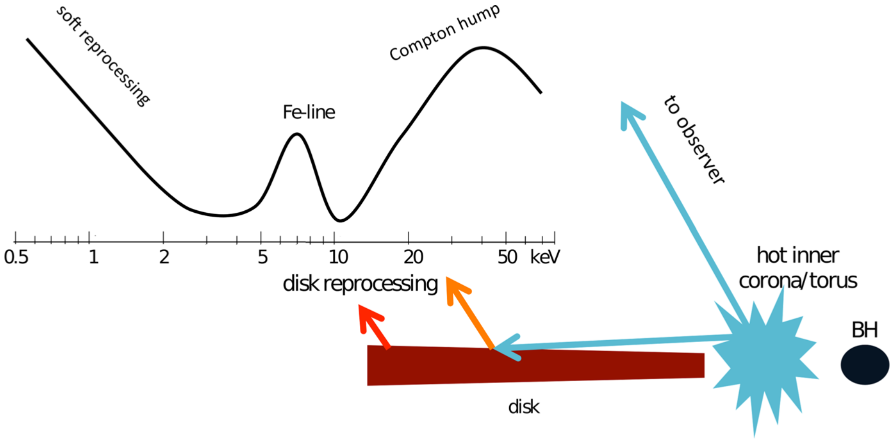


Fig. 5 A fraction of the X-ray emission from the inner hot corona/torus is intercepted by the disk and reprocessed with the approximate spectral shape displayed in this figure. At soft energies (< 2 keV) reprocessing is due to a number of spectral transitions plus disk heating, at energies of $\sim 4-7$ keV to Fe-Kα transitions, and at higher energies to the combined effect of photoelectric absorption and Compton scattering. Globally these features are often referred to as *reflection* features. Owing to light propagation delays, luminosity variations by the inner hot corona/torus are reverberated by the disk with increasing lags as the *illumination* front propagates outwards

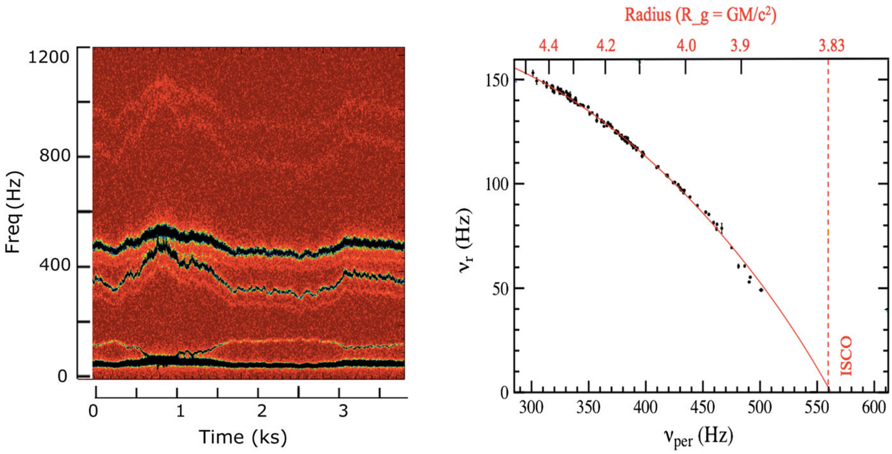


Fig. 6 Dynamical (time-frequency) colour-coded power spectra from a simulation of QPOs in a 1 Crab accreting BH of 7.1 $M_\odot$ and spin $a = 0.6$ seen at disk inclination of 63°. The simulation is for an ~ 8 m^2 LAD-type instrument and adopts QPO frequencies and amplitude in the range of those Fig. 2. The QPO mode identification and frequency evolution are based on the RPM [40], where LFQPOs are associated to nodal precession, and the two HFQPOs to periastron precession and azimuthal motion, respectively. The simulated signals arise from the emission of an elongated (315°) luminous region with radial extent of 0.5 R_g, in geodetic motion at radii that vary between 4.0 and 4.5 R_g with X-ray flux. QPO signals most clearly visible (from low to high frequency) are due to: nodal precession, radial epicyclic motion (note the inverse dependence on radius compared to all other frequencies), periastron precession, orbital motion; a few other combination frequencies are clearly detectable. The right panel shows the dependence of the LFQPOs on the lower frequency HFQPO, and the fit obtained by applying the RPM; radii are given on the upper X-axis, with the inferred ISCO radius shown by the dotted line (after [26])

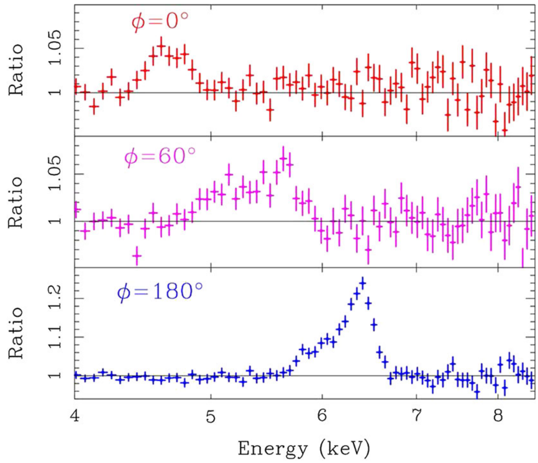


Fig. 7 Simulation of Fe-line profile variations caused by a bright line-emitting blob orbiting in the inner disk region of a 2.5 mCrab AGN. The figure show Fe-line profile ratios to line average for three different phase intervals, from two 10 ks orbits at 10 R_g around a 10^7 $M_\odot$ black hole with spin $a = 0.5$. The blob contributes 10% of the Fe line flux; the disk is seen under an inclination of 30° (after [26])

4 Combined Spectral/Timing Diagnostics

The energy resolution ($\sim$ 200 eV), range and extremely high effective area of solid state detectors planned for LOFT, eXTP and STROBE-X will afford measurements of spectral variations (besides flux variations) over the dynamical timescales of the innermost disk regions. Variations of the X-ray continuum components (e.g. those arising from *reflection*, see Fig. 5), as well as those of Fe-lines can be studied with high precision through the merging of spectral and timing diagnostics.

We note that (photon-starved) observations with the XMM/Newton satellite have already provided some evidence for Fe-line profile variations that arise from luminous *blobs* orbiting only a few Schwarzschild radii away from supermassive BHs in the nuclei of a few AGNs (e.g. NGC 3516 [19]). With an instrument like the LAD such variations can be studied with high S/N in dozens bright AGNs (see Fig. 7), thus mapping the velocity field of the accretion disk, and measuring relativistic light deflection and propagation effects in the strong field regime [26]. In this context timing information, e.g. the blob orbital period, provides absolute size measurements (cm, for instance), whereas velocity measurements, e.g. from the orbital Doppler modulation in the line profile, yields radii in geometrical units (R_g): BH mass is thus derived from the combination of the two. The timing/spectral signals of blobs orbiting at a few R_g's are most easily studied in bright AGNs, where individual cycles are detectable. This is a somewhat counter-intuitive mass-related effect: it arises because despite a $\sim$ 3 orders of magnitude lower X-ray flux at the earth, bright AGNs are characterised by a factor of $\sim 10^2 - 10^3$ higher number of photons at the earth per light crossing time (units of, say, $R_g/c \propto M$) than stellar mass BHs, owing to their factor of $\sim 10^5 - 10^6$ higher mass [37].

Nevertheless the Fe-line and flux variations from blobs orbiting the strong field regions of stellar mass BHs can be recovered over millions of High Frequency QPO (HFQPO) cycles (thus observations of order $\sim 10^4$ s) by resorting to energy-resolved cross-spectral Fourier techniques, in which X-ray continuum HFQPOs, with their very high S/N, effectively *phase* narrow energy intervals in the Fe-line profile, and single out the corresponding modulation [26]. This kind of spectral-timing techniques (and even polarimetric-timing techniques, see Sect. 5) which average fast variability signal over timescales much longer than dynamical timescales ($\gg 10^3$ typically) involve an effect that favors smaller mass BHs, thus partly countering the above-described *mass* effect. In fact a higher instrumental throughput translates into a higher S/N gain of combined spectral-timing (and polarimetric-timing) Fourier-based studies of stellar mass BHs, where the relevant fast variations are detected in the incoherent regime, than for supermassive BHs, whose variations are always in the coherent regime (for details see [18,44]). Simulations show that the energy and flux modulation due to orbiting blobs can be reconstructed accurately (e.g. to a few percent in the highest blue/redshifted energies) with tens of ks LAD observations of high luminosity stellar mass BHs, yielding key detailed information on Kerr geodesics in the strong field regime [26].

Light travel-time reverberation is also a very powerful spectral/timing technique, which can be exploited for investigating gravity with the new instrumentation. Fast flux variations in the hot central corona are *echoed* in the disk *reflection* components at progressively larger radii as the *illumination front* of each variation propagates outwards. The inner regions, where disk (red)shifts and velocities are highest, reverberate first: therefore the Fe-line wings will respond with very short delay. The bulk of the line profile, reprocessing at soft energies and Compton hump at higher energies respond with increasingly long lags [37,44]. Reverberation thus encodes GR effects in the motion of disk matter and photon propagation as a function of absolute radius. High precision measurements of BH mass and spin can also be obtained in this way.

Energy-dependent reverberation features detected in XMM/Newton observations of several bright AGNs present with limitations due to poor statistics [24]. The broad energy range covered with very-large-area solid-state instrumentation makes eXTP and STROBE-X ideally suited to carry out reverberation studies. In fact their payload comprises very high throughput detectors also in the soft X-ray band (the SFA and XRCA, respectively), besides the LAD.[2]

Figure 8 shows a simulation of the lags with which fast variations by the hot corona around a stellar mass BH are reverberated at different energies; observations with eXTP can measure the inner disk radius and thus BH spin to high precision [6]. This is but an example of the potential of X-ray reverberation for strong field gravity studies; much remains to be investigated also from the point of the analysis techniques and modeling.

5 Combined Spectral/Timing/Polarimetric Diagnostics

X-ray polarimetry of cosmic sources is still in its infancy. With the upcoming IXPE mission[3] [46] the field will enter a more mature phase, in which studies of some GR effects in the strong field regime become feasible (for instance the detection a varying

[2] The Athena mission, with its $\sim 1\ m^2$ X-ray optics, will also have reverberation capabilities though mainly in the energy range below ~ 10 keV [44]. It is planned for launch in the 2030s.

[3] To be launched in 2020.

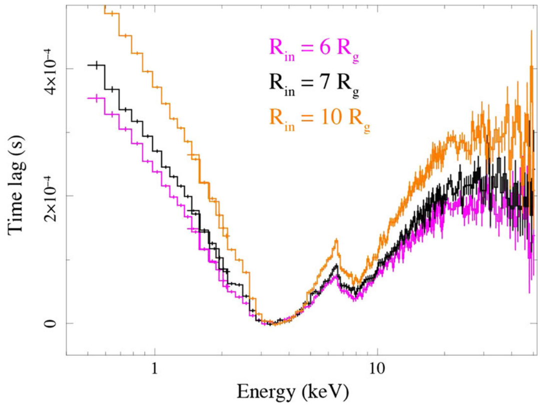


Fig. 8 Simulated lag versus energy spectrum of a 10 $M_\odot$ Schwarzschild BH with a flux of 1 Crab as observed with the SFA and LAD instruments planned for eXTP. The lags originate from light-propagation delays in the disk *reflection* component; they are calculated over the 50–150 Hz range by using Fourier cross-spectra in each energy bin with respect to a broad band (2–20 keV). Different components of the *reflection* spectrum (see Fig. 5) are characterized by different lags and allow mapping of the velocity fields, geometry and absolute scale of the inner disk regions. The curves corresponding to three different inner disk edges are clearly resolved [6]

polarization degree and angle as a function of energy in the thermal radiation emitted at different radii from the innermost disk regions around BHs [7]). However, IXPE cannot merge polarimetry with spectral-timing diagnostics, as it does not include a large area X-ray detectors in its payload.

On the contrary eXTP's unique polarimetric and high throughput capabilities will enable studies which combine spectral, timing and polarimetric diagnostics. An example of application of such powerful combination has been worked out already in some detail, building on the evidence that frame-dragging-induced nodal precession (Lense-Thirring precession in the weak field limit) takes place in the hot innermost region/corona of accretion flows towards NSs and BHs (Fig. 9) [14,38]. The variable low frequency QPOs (LFQPOs) observed in NSs and BHs of stellar mass arises from geometrical effects likely due to the varying obscuration of the precessing corona/torus by the inner rim of the optically thick disk. Such geometry implies also that the illumination pattern of the disk by the corona varies in azimuth as a result of precessional motion (see [16] and references therein). Therefore *reflection* features by the approaching (blueshifted) and receding (redshifted) sides of the disk are modulated with LFQPO phase. Characteristic changes are thus imprinted which encode information on matter motion and photon geodesics in strong gravity.

Some evidence for Fe-line variations modulated at the QPO frequency has been found in a BH binary displaying very slow LFQPOs, but conclusions were hampered by poor statistics [17]. The eXTP/LAD with its very high throughput will afford studying individual LFQPO cycles (or alternatively trains of cycles during which coherence is maintained) of the X-ray continuum in virtually all known QPO systems. This will enable *phasing* of the LAD data in the Fe-line energy range with the LFQPO modulation, so that very high S/N precession-phase-resolved line profiles can be accumulated.

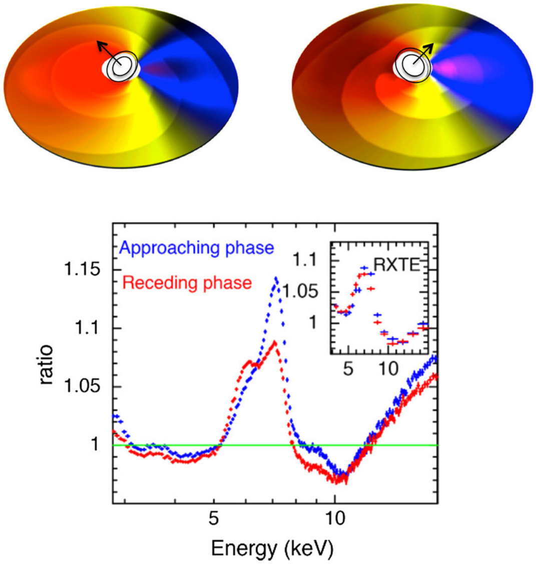


Fig. 9 Simulation of the Fe-line profile changes resulting from nodal, frame-dragging driven precession of the hot inner corona/torus, which leads to illumination of different regions of the disk at different precession phases (as illustrated in the two top drawings). The simulation refers to a 50 ks observation of a bright stellar mass BH (GRS 1915+105) with the instrumentation planned for eXTP. The disk inner radius and inclination are 30 R_g and 70 deg. LFQPOs at the precession frequency of 0.46 Hz in the continuum emission result from varying occultation of the precessing corona/torus by the disk. The LAD LFQPO signal is used to carry out phase-resolved spectroscopy of the Fe-line in 20 intervals. The profiles in the figure are from the two phase intervals in which the illumination of the approaching (blue) and receding (red) regions is highest (the continuum spectrum from the hot corona/torus has been subtracted); changes are resolved with very high significance [6]

Figure 9 shows the change in the Fe-line profile at the LFQPO phase corresponding to maximum illumination of the approaching (blue) and receding (red) disk sides. The same *phasing* technique, when applied to the data of the eXTP/PFA will reveal variations of the polarisation degree and angle with the LFQPO phase, which originate in the same coronal geometry changes that give rise to the QPO modulation. Such polarisation variations encode also information on the way polarization vectors propagate in strong field gravity, thus providing an additional important diagnostic tool [15] (see Fig. 10).

In HFQPOs from orbiting blobs a modulation of the polarization degree and angle is also expected, which carries additional geometrical and physical information about strong gravitational fields. The application of cross-spectral Fourier techniques similar to those devised to study Fe-line variations at the HFQPO frequency will enable extraction of the polarisation HFQPO signal from the eXTP/PFA [18].

6 X-ray Diagnostics and Alternative Gravity Theories

As summarised in the previous sections X-ray diagnostics and techniques that can effectively measure spacetime properties in the strong field regime, will be fully

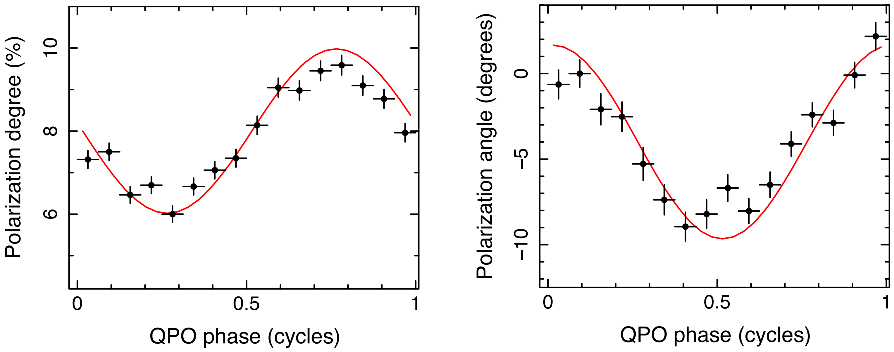


Fig. 10 Simulation of the modulation in the polarization degree and angle arising from the precession of the inner corona as measured by the polarimeter planned for eXTP in conjunction with QPO phasing from the LAD. Parameters of the simulations are comparable to those in Fig. 9 [6]

exploited with future instrumentation; they provide analogous settings within which comparative studies of BHs ranging from ~ 10 to $\sim 10^9$ $M_\odot$ can be carried out. Spacetime curvature close to the event horizon of supermassive BH is comparable to that of classical GR tests in the solar system and double NS relativistic binary pulsars; close to stellar mass black holes spacetime curvature is instead $\sim 11-16$ decades higher (see Fig. 11). GR geodesics, once rescaled by mass, are insensitive to spacetime curvature. In general, that is not the case in alternative theories of gravity. For instance the GR motion of light and matter around, say, a 10^7 $M_\odot$ BH in an AGN with a given value of its spin (say $a = 0.5$), is identical to that around a 10 $M_\odot$ BH with $a = 0.5$ in an X-ray binary, if time and space coordinates are simply rescaled. Yet the curvature of spacetime around two such black holes at a given radius (R_g units) would differ by a factor of 10^{12}.

If no departure is found in the motion of light and matter across BHs of vastly different masses, then X-ray diagnostics would provide an unprecedented confirmation of the correctness of GR predictions in the strong field regime. At the same time constraints on a variety alternative gravity theories would be obtained. Conversely if departures are found which survive intense scrutiny for effects that might alter purely geodetic motion (e.g. hydrodynamical, MHD or radiative transfer effects), then evidence for new physics would gathered. In general alternative gravity theories are tested (or constrained) by their ability to generate metrics whose properties match those obtained observationally. Two approaches are often adopted to introduce modifications to GR.

In the bottom-up-type approach phenomenological parametrisations of the space-time are used. Gravity tests in the solar system and relativistic radio pulsar binaries have largely adopted such an approach, with values of metric parameters (such as Parametric Post-Newtonian or Post-Keplerian parameters) constrained through observations, without resorting to underlying assumptions about the theory of gravity. X-ray diagnostics address the properties of the strong gravitational fields of compact objects; there exist parametric extensions of the Kerr metric which are useful in such a regime. In particular, one can expand a stationary, axisymmetric metric around a compact

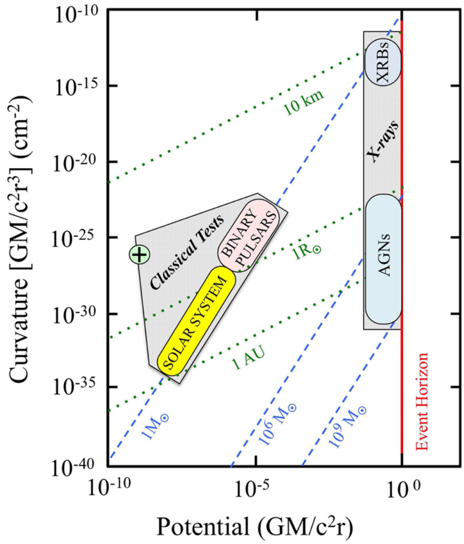


Fig. 11 Figures 2–11 X-ray diagnostics, such as relativistic Fe-lines and QPOs, measure gravity effects in the *stationary* spacetimes near NSs and stellar mass BHs in X-ray binaries and near supermassive BHs in AGNs, exploring regions with gravitational potentials of $GM/c^2r \sim 0.1$ or higher. Instead classical GR tests are limited to potentials ~ 4 to ~ 8 orders of magnitude weaker. Stellar mass and supermassive BHs present with a huge difference in their spacetime curvature of typically 11–16 decades (for a given potential): this has implications for testing alternative gravity theories which, unlike GR, are sensitive to spacetime curvature (after [32])

object in terms of its multipole moments and then use X-ray diagnostics to measure at least the three lowest terms, i.e. the monopole (which corresponds to the BH mass), the dipole (which correspond to the BH spin), and the quadrupole. According to the *no-hair theorem*, the quadrupolar term of a BH in GR is determined uniquely by its mass and angular momentum [22,35]. Modified Kerr-like spacetimes with arbitrary multipole moments have been developed (see e.g. discussion in [20]). Geodesic motion in these proposed metrics has been calculated and some applications to gravity tests exploiting Fe-line profiles and QPO signals have been discussed [2,3,21,23].

First-principle modifications of GR are adopted in the top-down approach. Theories of gravity which include a quadratic term of the curvature tensor coupled to a scalar field are especially relevant and yet largely untested, as they modify gravity in the strong-field/large-curvature regime, while leaving the weak field limit (which has been extensively tested) virtually unaffected. Some calculations have been carried out in the context of Einstein–Dilaton–Gauss–Bonnet gravity and Dynamical ChernSimons gravity [27,28]. It is found that the fundamental frequencies of geodesic motion close to rotating BHs in these theories differ from their GR equivalents by up to several percent. Such differences are well with reach of the X-ray QPO measurements that LAD-type instrument will obtain.

7 Conclusions

The instrumentation planned for next generation X-ray astronomy missions devoted to very high throughput observations provides a new perspective in the study of the strong and *stationary* gravitational fields in the close vicinity of accreting BHs (see also [6]). Powerful diagnostics, such as relativistic Fe-lines, QPOs and polarisation, will be exploited over the whole range of BH masses and their variations investigated over dynamical timescales of matter motion down to a few R_g's away from the event horizon. The application of tomography and reverberation techniques to spectral/timing and spectral/polarimetry/timing measurements will be extremely important in this regard. More advanced modeling and calculations in full GR (and possibly also in alternative gravity) must be developed in order to further explore these techniques' potential and single out more *observables* which can be directly compared to the predictions of gravity theories in the strong field regime.

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