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### Executive Summary of White Paper (5000 character limit)

Neutron stars and black holes (compact objects) are among the most fascinating and puzzling objects in the Universe.  They uniquely provide an environment to test the laws of physics at their extremes, as density in a neutron star reaches values several times higher than nuclear density, magnetic fields are billions of times higher than the Sun's, and gravity around black holes is so strong as to trap light itself. Compact objects, however, do not like to reveal their secrets all at once. Fifty years after their discovery, we still do not know what neutron stars are made of, and the question of how black holes modify space and time around them is still open. The X-ray emission of compact objects presents a rich phenomenology that can lead us to a better understanding of their nature and to address more general physics questions, like:Does general relativity (GR) apply in the strong gravity regime? Is spacetime around black holes described by the Kerr metric?What are the masses, radii and composition of neutron stars and their atmospheres?
Recent advancements in transition-edge sensors (TES) present a unique opportunity to open a new window on compact objects: high energy-resolution spectroscopy combined with high-precision timing and high sensitivity.

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# 1 Introduction

Neutron stars and black holes (*compact objects*) are among the most fascinating and puzzling objects in the Universe. They uniquely provide an environment to test the laws of physics at their extremes, as density in a neutron star reaches values several times higher than nuclear density, magnetic fields are billions of times higher than the Sun's, and gravity around black holes is so strong as to trap light itself. Compact objects, however, do not like to reveal their secrets all at once. Fifty years after their discovery, we still do not know what neutron stars are made of, and the question of how black holes modify space and time around them is still open.

The X-ray emission of compact objects presents a rich phenomenology that can lead us to a better understanding of their nature and to address more general physics questions:

- ◇ **Does general relativity (GR) apply in the strong gravity regime? Is spacetime around black holes described by the Kerr metric?**
- ◇ **What are the masses, radii and composition of neutron stars and their atmospheres?**

The question whether GR applies to compact objects has very profound implications. Most of our fundamental theories in physics have a range of applicability and break down at some particular scale. For example, electroweak theory separates into electromagnetism and weak theory at energies lower than about 200 GeV, while strong and electroweak theories are thought to unify at very high energies. Since most of the current tests of GR are performed in the weak gravitational fields present in our solar system, the 6 to 7 orders of magnitude higher gravitational potential and $\sim$20 orders of magnitude greater curvature (Baker et al., 2015) found around compact objects offer the tantalizing prospect of finding new gravitational physics in strong fields.

Much progress has been made in this sense in the field of gravitational waves. However, the wavelength of gravitational waves is necessarily comparable to the size of the colliding objects, which limits the scope for probing in detail the spacetime surrounding compact objects; thus, electromagnetic signals provide a crucial complementary window into strong gravity. One of the most subtle consequences of GR is the "no-hair" theorem, by which black holes can be fully characterized by their mass, angular momentum and charge. Since we expect no charge on astrophysical black holes, the spacetime that surrounds a black hole can be nearly exactly described by the Kerr metric. The only way to test this theorem is to probe the spacetime very close to the hole. Fortunately, the X-ray emission of accreting black holes carries information about the inner region of the accretion disk, within a few gravitational radii ($R_g = GM/c^2$) from the hole, encoded in the fast variability of its spectrum. In particular, the emission from the accretion flow very close to accreting compact objects presents two possible high-precision diagnostics of their spacetime: reverberation mapping and quasi-periodic oscillations (QPOs).

Variability in the X-ray emission from accreting compact objects also carries information on the accretion processes themselves. Accretion disks and jets are ubiquitous in astrophysics. They are found around newborn stars, during planetary formation, in active galactic nuclei (AGNs), in which they play a key role in shaping the evolution of galaxies. However, the mechanisms for angular momentum transport in the disk and for jet formation close to the central object are poorly understood. As for any type of physics, studying accretion at its most extreme actualization, the inner accretion disk close to compact objects, provides the best opportunity for breakthroughs in the understanding of the phenomenon as a whole. For example, the high magnetic field expected to be present in the disk of accreting stellar mass black holes and neutron stars, could make it easier to highlight the role of magnetic fields in generating the viscosity needed for accretion to occur. Or the role of the black hole spin in powering winds and jets can be better understood once we measure the spins of many black holes.

The density reached in a neutron star's core, several times higher than nuclear density, is not reached anywhere else in the universe at cold temperatures, let alone in our terrestrial physics labs, and therefore neutron stars represent the only laboratory available to look for the equation of state for cold, dense matter. The holy grail of neutron star observations, the mass-radius relation, if measured for several neutron stars, could put stringent constraints on the equation of state (Steiner et al., 2013). Mass measurements of massive neutron stars exclude a number of equations of state that predict a relatively soft dependence of pressure on density. Although a number of masses of neutron stars have been measured with high precision, especially for compact binaries, radius measurements are much harder to achieve with the precision of less than a kilometer required to put stringent constraints on the equation of state.

The advent of moderately high-resolution X-ray spectroscopy with *Chandra* and *XMM* promised to usher in a new age in the study of neutron stars: we thought we would study neutron stars like stars, with resolved absorption spectra revealing their surface chemical composition and physical conditions (e.g. surface gravity, pressure, temperature). Nature, however, did not cooperate in this endeavor, as high-spectral-resolution observations of neutron stars have not revealed verified atomic absorption lines yet. Still, hints of the presence of absorption lines have been detected in accreting and isolated neutron stars, and the advent of high energy-resolution spectroscopy in the X-rays could still bring the detection of narrow and weak absorption features.

Recent advancements in transition-edge sensors (TES) present a unique opportunity to open a new window on compact objects: high energy-resolution spectroscopy combined with high-precision timing and high sensitivity. TES-based detectors can already achieve an energy resolution of less than an electronvolt at about 1.5 keV, and of about 2-3 eV at 5-10 keV (Morgan et al., 2017). Furthermore, the arrival times of the photons can be measured to a precision of 300 ns or better with a short deadtime of less than a millisecond on a given TES array element (Morgan et al., 2016). In the context of ongoing missions, with the current TES technology it is possible to achieve the timing resolution of the best timing telescope in space right now (*NICER*, with a resolution of 100 ns) while reaching an energy resolution more than 40 times better than *XMM-Newton* (130 eV at 6 keV), and there is still space for improvement. The Canadian Space Agency recently funded an 18-month concept study for a TES-based telescope, *Colibrì*, that started in September, 2018. *Colibrì* will be dedicated to the study of compact objects in the X-ray, and will pair TES-based detectors with collector optics to achieve a high throughput ($\sim$100kHz count-rates).

## 2 Reverberation mapping

Spectral analysis of the X-ray emission from accreting black holes can provide insights on the dynamics of the regions close to the hole, as gravitational redshifts from the black hole and relativistic motion of the orbiting plasma in the inner accretion disk distort the spectrum. However, a deeper understanding can be reached by combining spectral with timing analysis, as much information is carried by the variability of the spectrum. The emission from accreting black holes is observed to come from different components: the direct emission from an accretion disk, which emits thermally in the soft X-rays for black hole binaries and in the optical and UV bands for AGNs (Shakura & Sunyaev, 1973; Novikov & Thorne, 1973); the emission from a compact, optically thin corona above the black hole, which produces a power-law spectrum in the hard X-rays (Thorne & Price, 1975; Sunyaev & Truemper, 1979); and finally a reflected component, made by high-energy photons from the corona that are scattered back into the line of sight by the disk, and that presents an iron K$\alpha$ fluorescence line at 6.4 keV and a reflection hump that peaks at $\sim$30 keV (Ross & Fabian, 2005; García et al., 2013).

With a fine enough timing resolution, the reflected emission can be used to map the inner region of the accretion disk. Emission from the corona shows a rapid aperiodic variability, on timescales of milliseconds for stellar mass black holes and of minutes for AGNs. This variability gets reflected in the reverberation signal with a light-crossing time delay (Uttley et al., 2014), with time delays of the order of a few hundreds of microseconds for Galactic binaries, and much longer for AGNs (scaling as $\propto M$). Also, as different parts of the accretion disk will be illuminated in subsequent times, photons of different energy will present different time delays, reflecting the characteristic Doppler shift of the reflection region. Such reverberation lags have been detected in several AGNs with *XMM-Newton* and *NuSTAR* (Zoghbi et al., 2012; Kara et al., 2016), and very recently in the X-ray binary MAXI J1820+070 with *NICER* (Kara et al., 2019).

Observations so far are limited by either the low sensitivity or low timing resolution of current X-ray telescopes. High-resolution spectral fitting of the X-ray emission, especially of the Fe-line profile, provides information on the strong-field gravity effects on the orbiting plasma and its dynamics, from which radii can be inferred in units of the gravitational radius, as well as the spin of the black hole and the inclination angle of the system. The possibility of performing reverberation mapping, which yields distances in absolute units given by the light travel time, simultaneously to spectral fitting would therefore provide a test of the Kerr metric itself, as well as a measurement

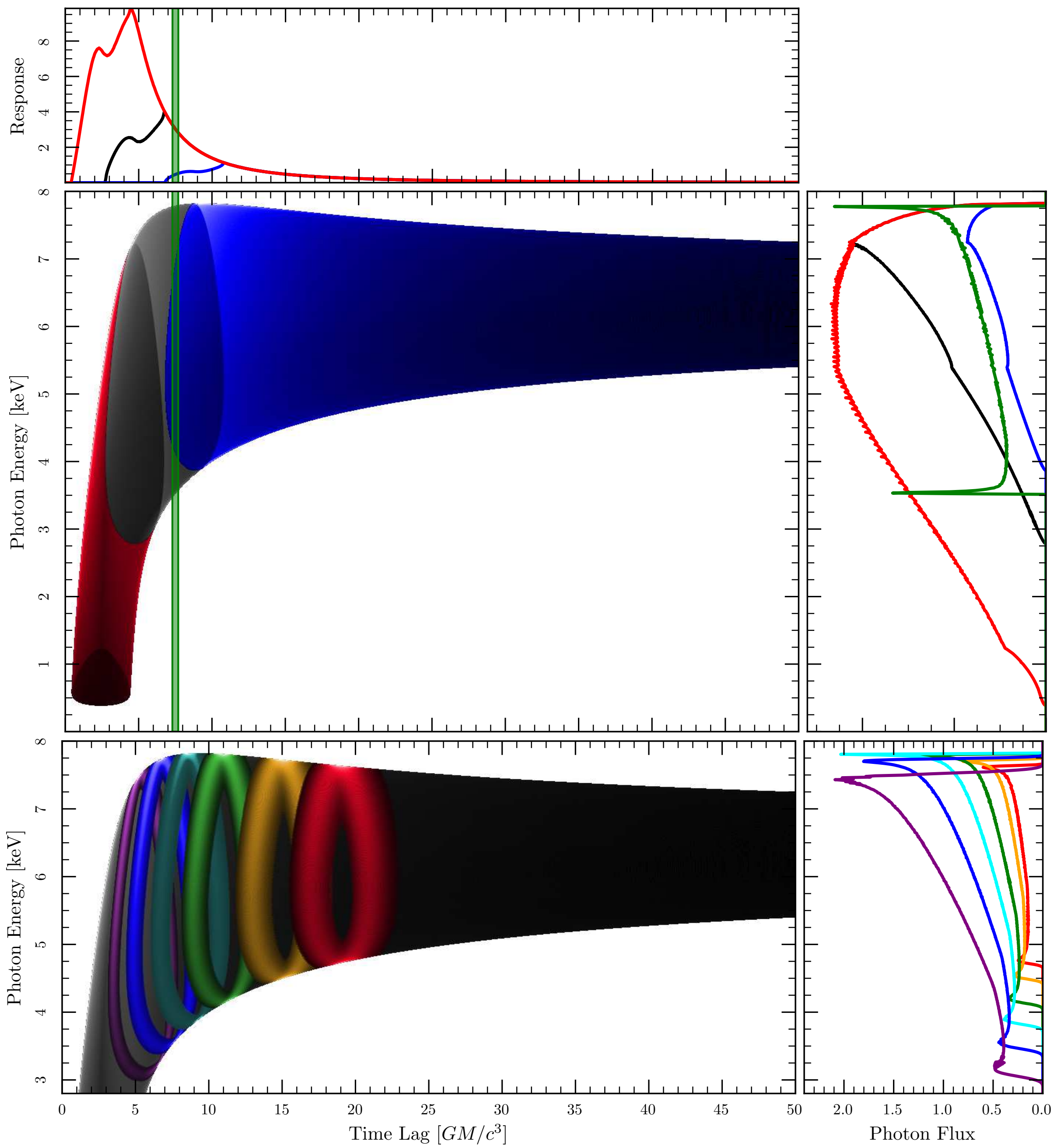


Figure 1: Energy- and time-dependent reflected emission resulting from a $\delta$-function (the iron line) in the driving continuum for a black hole with spin parameter $a/M = 0.998$. The corona is modelled as a point source along the spin axis at $z = 2GM/c^2$ (lamppost), and the observer is located at an inclination of $86°$. See also Mastroserio et al. (2018). **Upper part:** *Central panel.* Reverberation response spectrum for the accretion disk ending at the ISCO (red), $4GM/c^2$ (black) and $8GM/c^2$ (blue). *Upper panel.* Energy integrated flux. Photons of different energies, coming from different radii on the disk, also arrive at different times. *Right panel.* Time integrated spectrum. The caustics form at the edge of the response function as can be seen in the reverberation spectrum measured a particular time lag (green). **Lower part:** *Central panel.* The colored regions depict the reverberation signal from parts of the disk where a QPO of $Q \sim 10$ and the nodal precession frequency of 1, 2, 5, 10, 20 and 40 Hz would exist for a 10 $M_\odot$ black hole, assuming the RPM model. *Right panel.* The caustics can be seen in the reflection spectrum measured for a particular QPO.

of the mass of the compact object (Hoormann et al., 2016; Jiang et al., 2016). Although the total spectral features of reverberation are relativistically broadened in general, high energy and timing resolution combined would allow slicing the emission in both the spectral and time domain, which could reveal sharp features, broadened not by the bulk motion of the disk material but by thermal and turbulent motion within the disk with $v/c \sim 10^{-3}$ or smaller as shown by the green curves in Fig. 1.

## 3 Quasi periodic oscillations

QPOs are nearly periodic fluctuations commonly observed in the X-ray light curve from the inner regions of accreting compact objects (Miyamoto & Kitamoto, 1991; Takizawa et al., 1997; van der Klis, 2005, 2006b). The first to be discovered were the low frequency QPOs (LFQPOs), with frequencies $\sim 0.1 - 30$ Hz. *RXTE* revealed higher frequency features: high frequency QPOs (HFQPOs) in the range $\sim 40 - 450$ Hz from black hole systems (Morgan et al., 1997), and kHz QPOs in the range $\sim 300 - 1200$ Hz in neutron star systems (van der Klis, 2000, 2005). The origin of QPOs is still debated, but their frequencies are commensurate with those of orbital and epicyclic motions in the Kerr metric close to the compact object, and thus constraining the QPO mechanism would provide a new way to measure properties of the inner accretion flow and the effects of strong gravity.

Current models for LFQPOs find their origin either in some instability in the accretion flow, or in a geometric oscillation (Chakrabarti & Molteni, 1993; Stella & Vietri, 1998; Stella et al., 1999; Tagger & Pellat, 1999; Wagoner et al., 2001; Schnittman et al., 2006; Ingram et al., 2009; Cabanac et al., 2010) such as, most notably, Lense-Thirring precession (Stella & Vietri, 1998; Stella et al., 1999; Schnittman et al., 2006; Wagoner et al., 2001; Ingram et al., 2009). This is a nodal precession of orbits inclined to the equatorial plane caused by a spinning compact object dragging the surrounding spacetime around with it (the frame dragging effect). The origin of HFQPOs and kHz is more obscure, with the proposed models including Doppler modulation of orbiting hotspots in the inner disk, oscillation modes of a pressure-supported torus, nonlinear resonances, gravity and pressure modes in the accretion disk (Lai et al., 2013; Belloni & Stella, 2014, and references therein) and, for the case of neutron stars, beating with the neutron star spin frequency (van der Klis, 2006a).

It is clear that new and better observations are needed to understand these phenomena and ultimately exploit them as diagnostics. LFQPOs are normally detected with high significance using current instruments, thanks to their high amplitudes. This enables studies of the QPO phase dependence of the spectral shape (i.e. QPO tomography) (Ingram et al., 2016, 2017). Instruments such as *Colibrì* will revolutionize such studies by providing vastly better spectral resolution and dramatically higher count rates, particularly considering that instruments such as *XMM-Newton* (and *ATHENA* in the future) are limited by photon pile-up and therefore cannot be used to observe the brightest sources. Furthermore, the unprecedented count rates will for the first time enable similar tomographic analyses with HF and kHz QPOs, providing a qualitatively new way of testing models. HFQPOs are much fainter than LF, and this explain the scarcity of current detections. The high sensitivity of *Colibrì* will enable the detection of HFQPOs in more systems and it will test the presence of the even weaker signals predicted by some of the current theoretical models. The observed HFQPOs with RXTE show a similar set of frequencies from all the sources. This may be a selection effect from the *RXTE* band, or it could mean that HFQPOs are excited only at specific frequencies. A higher sensitivity and timing resolution could bring to the detection of additional signals or to a null detection at higher frequencies, allowing to discern between the proposed models.

As an example of the power of QPOs as diagnostic, Fig. 2 shows the results of a simulation for a HFQPO on a 10 $M_\odot$ BH rotating at 95% of the critical spin performed for *Colibrì*, where the relativistic precession model (RPM) for HFQPOs was assumed. In the RPM, four signals are expected in the power spectrum: Lense-Thirring precession, radial epicyclic motion, periastron precession and orbital motion, and the relation between the frequencies is uniquely determined by the Kerr metric. A drift in the frequencies is observed, correlated to a variability in the flux, that is interpreted in the RPM as a response to a change in the inner radius of the disk. Observations of the four signals and of how they drift, not only would shed light on the origin of the phenomenon, it would constrain the mass and spin of the hole with great accuracy, as shown in Fig. 2. Furthermore, since mass and spin are the only parameters important in describing the spacetime around a black hole in the Kerr metric, these observations

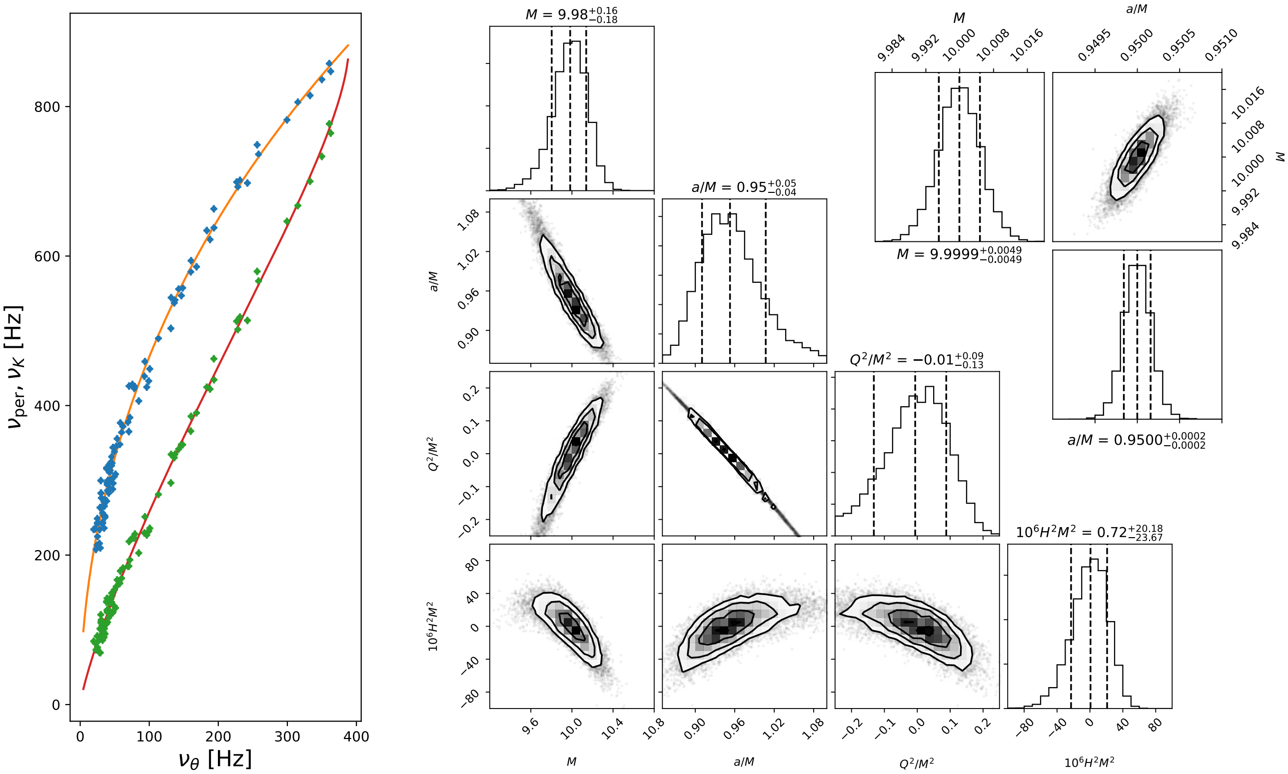


Figure 2: Simulation of HFQPOs for *Colibrì*, assuming the RPM model for a black hole with spin parameter $a = 0.95$, $M = 10$ $M_\odot$ assuming a measurement error on the frequencies of 5 Hz. The blue points depict the orbital frequency ($\nu_K$) and the green show the frequency of periastron advance ($\nu_{\rm per}$), both as a function of the node precession frequency ($\nu_\theta$). The input model is the Kerr metric; the simulated frequencies are used to constrain deviation from Kerr metric by adding a cosmological constant and electric charge to the black hole.

could provide constraints on deviations from it. In Fig. 2 a simple test is shown: adding a charge or a cosmological constant, both expected to be negligible in astrophysical black holes, changes the metric from Kerr; finding a value different from zero would hint to a deviation from the Kerr metric and from GR.

## 4 High energy-resolution, high-throughput spectroscopy of the neutron star surface

Due to the high surface gravity of neutron stars, the elements in neutron star atmospheres stratify within 30 seconds, leading to a photosphere made from only the lightest element present, typically hydrogen. In most neutron stars, some amount of accretion (from a companion star, the interstellar medium, or fallback from the supernova) will have occurred, so featureless (in the X-ray) hydrogen atmospheres are generally expected (e.g. Ho et al., 2007). However, a variety of elements may be present in the photospheres of neutron stars, if the neutron stars are actively accreting. On rapidly spinning neutron stars, spectral lines will be spread out by the Doppler shift; therefore, detecting and measuring the energy and width of the spectral lines from a rotating neutron star would directly provide an estimate of the neutron star radius, if the spin period is known (Özel & Psaltis, 2003). In general, rapid rotation may make the lines too broad to be detected. However, the narrow *cores* of these broad lines may be deep enough to be clearly detected with appropriate throughput and spectral resolution (Bauböck et al., 2013). Some X-ray binaries have relatively low spin (e.g. Terzan 5 X-2, Strohmayer & Markwardt, 2010), and/or very low inclination, either of which would narrow the lines enough for possible detection (Yoneda et al., 2018).

During active accretion episodes, the surface of the neutron star is generally not visible, as photons from the

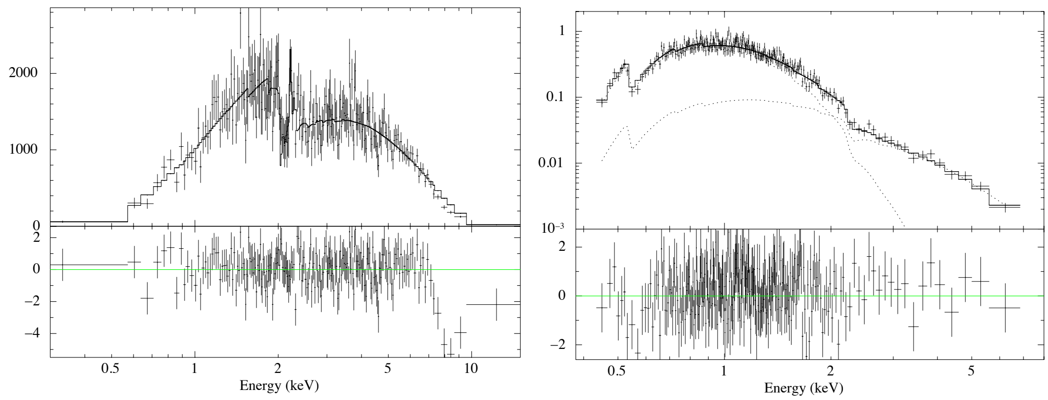


Figure 3: Left: Simulated observation with *Colibrì* during the cooling tail of a X-ray burst exhibiting an absorption edge at 7.5 keV. Right: Simulated observation with *Colibrì* of quiescent Aquila X-1 showing an absorption feature at 0.55 keV.

stellar surface are Comptonized by the accreting material. Type-I X-ray bursts and carbon superbursts represent an exception, as thermonuclear reactions on the surface of the star dramatically increase the emission from the surface itself, so it dominates the emission for a few seconds to hours. Cottam et al. (2002) identified absorption lines in the sum of *XMM-Newton* spectra over many Type-I X-ray bursts from EXO 0748-676, which they argued were redshifted Fe lines from the stellar surface. This particular source is now thought to be rotating rapidly (Galloway et al., 2010), which makes it challenging to explain the relatively narrow spectral features that they found (Lin et al., 2010; Bauböck et al., 2013).

However, several X-ray bursts since then have shown evidence for broader features, likely due to heavy nuclear burning products being mixed up to the photosphere in particularly energetic bursts (Weinberg et al., 2006). These include observations of a likely edge around 7.5 keV in HETE J1900.1-2455 by RXTE (Kajava et al., 2017), and around 8 keV in GRS 1747-312 by RXTE (Li et al., 2018). However, RXTE's spectral resolution was insufficient to clearly identify the spectral feature. High-throughput TES arrays will have the spectral resolution to clearly resolve edge features such as these, and the effective area to spot them in short time periods ($\sim$ 1 s), allowing robust determination of the surface redshift of these bursting neutron stars (see Fig. 3).

These particular observations are hard for planned instruments such as the *X-IFU* on *ATHENA* (Barret et al., 2016), because of photon pile-up, but straightforward for instruments with collector optics. The count rate during X-ray bursts will peak at about 1-10 kHz (scaling from *RXTE* results, Galloway et al., 2008) for *ATHENA* and *Colibrì*, which both plan to use TES X-ray detectors for spectroscopy. In the case of *ATHENA*, if two photons arrive within 2.6 ms from each other on the same pixel, the energy measurement of the second photon will be significantly degraded. The expected count rates for X-ray bursts dramatically exceed this limit, and therefore, without blocking filters to reduce the effective area to the level of *XMM-Newton* or deliberate defocusing, *ATHENA* cannot easily perform spectroscopy during X-ray bursts. On the other hand, because a mission with collecting optics such as *Colibrì* builds effective area by having many collectors operating in parallel, with each collector focusing X-rays on several elements of a TES array, its nominal configuration can achieve high-resolution spectroscopy to count rates well beyond 100 kHz.

Low-mass X-ray binaries during quiescent periods between outbursts also exhibit surface features. If no accretion is occurring, then the photosphere will contain only the lightest element (typically H or He), and no lines will be present. However, if accretion onto the neutron star exceeds $\dot{M} \sim 10^{-13}\mathrm{M}_{\odot}$/year (corresponding to $L_X \sim 10^{33}$ erg/s), it is likely that metals will substantially populate the photosphere. Evidence for metal features in the photosphere of the quiescent LMXB Aquila X-1 was produced by Rutledge et al. (2002) from one (of several) Chandra observations. However, Chandra's spectral resolution and low-energy calibration left the nature of this feature in some doubt. High-energy resolution TES detectors would permit clear identification of these spectral features (see for example the case of *Colibrì*, in Fig. 3), likely within the context of a program to monitor the cooling of neutron

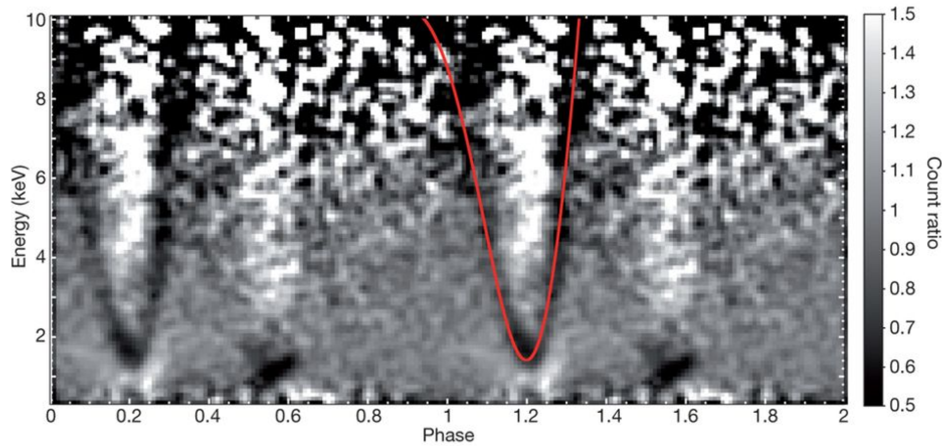


Figure 4: Phase resolved spectra from SGR 0418+5729 with the EPIC instrument on XMM-Newton. The red curve depicts the line centroid from a model in which radiation from the surface is absorbed by protons through the cyclotron resonance in a baryon-loaded current loop above the surface of the neutron star. Figure from Tiengo et al. (2013).

star crusts after an outburst (Wijnands et al., 2017), when occasional burps of accretion are often observed.

# 5 High-energy-resolution, high-time-resolution spectroscopy of the neutron star surface

Many neutron stars are also rapidly rotating. Observing phase-resolved spectral features adds the requirement of high-time-resolution to high-throughput. Rotation imparts a particular pattern in the observed X-rays as a function of energy and phase. In particular, if only a portion of the surface is emitting, hard X-rays will lead softer ones (Ford, 1999), and if the emission pattern is known or can be constrained from observations as it could be in Type-I X-ray burst oscillations (Heyl, 2005), one can constrain the mass and radius of the neutron star (Psaltis et al., 2014; Ozel et al., 2016). The boost in effective area of large collector based telescope with TES arrays relative to *NICER* will allow us to study fainter objects in shorter times and to derive constraints from ensembles of Type-I X-ray bursts with oscillations. The dramatic increase in energy resolution will probe and constrain the underlying emission models, reducing potential systematic errors in the determinations of mass and radius.

The rapidly rotating (3.15 ms) and massive ($1.97 \pm 0.04 M_{\odot}$) pulsar PSR J1614-2230 is an excellent target (Miller, 2016) for high-time-resolution spectroscopy. Pulsations have been detected by NICER (Wolff et al., 2019), however it is somewhat too faint for a long targeted NICER observation that would constrain the neutron star's radius from a detailed analysis of its pulse profile. Observing PSR J1614-2230 with greater effective area could yield powerful constraints on the radius of this neutron star as well as the emission mechanism to control systematics. Given that this is a faint source, pile-up is not an issue. Because the field of this star is weak and it has not recently accreted, we do not expect to see spectral features, so the high-energy resolution is not crucial.

Strong evidence for spectral lines has been found for several slowly rotating neutron stars with stronger magnetic fields. The XDIN RX J1308.6+2127 exhibits a spectral feature at about 740 eV with an equivalent width of about 15 eV (Borghese et al., 2017) over only a portion of its rotation. Unfortunately, the energy resolution of the EPIC-pn instrument on XMM-Newton is insufficient to resolve the line. A comprehensive analysis of the available data for the XDINS with XMM-Newton yields upper limits on the equivalent width of narrow (unresolved lines) of 10-50 eV, depending on the source and the duration of the available observations. A TES spectrometer (with energy resolution of about 1 eV) with a similar effective area to XMM-Newton would yield constraints ten times stronger for similar observing times.

Magnetars are among the most magnetic compact objects in the Universe. Their high energy properties and spin parameters point to a super-strong magnetic field of the order of $10^{14} - 10^{15}$ G. Spectroscopy provides a direct diagnostic of their total surface magnetic field strength. While their electron cyclotron features would fall in the MeV band, their proton cyclotron lines fall in the X-ray band. To date, we have evidence, initially mostly from the RXTE satellite and more recently from just a few observations with operating X-ray missions, of sporadic detections of spectral features in magnetars X-ray spectra. While the interpretation of these lines is still being debated, and their detection occurred either during an outburst or in quiescence, they have been mostly interpreted as proton cyclotron features from a magnetar-strength magnetic field, confirming in many cases the high magnetic field value inferred from spin-down measurements, e.g., 5 keV absorption line from SGR1806-20 (Ibrahim et al., 2002); 8.1 keV absorption line from 1RXS J170849-4009104 (Rea et al., 2004); 4 keV and 8 keV emission lines from 4U 0142+62 (Gavriil et al., 2008). More recently a variable absorption feature near 2 keV was discovered in a phase-resolved spectroscopy (Fig. 4) of the magnetar SGR 0418+5729 whose spin properties point to a much lower, below the QED value, magnetic field ($6 \times 10^{12}$G), supporting high-order multipolar field components (Tiengo et al., 2013). The line, when interpreted as a proton cyclotron feature, yields a magnetic field ranging from $2 \times 10^{14} - 10^{15}$ G. This suggests that spectroscopy can directly probe the topology of the magnetic field, and in ways that can not be done with timing which infers the dipole field strength. Unfortunately, the XMM-Newton EPIC instruments have insufficient energy resolution to resolve the feature. Furthermore, the data depicted in Fig. 4 hint of a second feature on the opposite hemisphere of the star. Observing similar lines in more neutron stars and with higher sensitivity could reveal the structure of the magnetic field and how magnetars work.

While early theoretical predictions suggested relatively wide absorption lines (e.g. Zane et al., 2001; Ho & Lai, 2001) as observed in some of the magnetar bursts' spectra, vacuum polarization has been subsequently suggested to suppress the strength of the proton cyclotron resonances in strongly magnetized plasma (Lai & Ho, 2002; Özel, 2003). This could reduce the line equivalent width by nearly an order of magnitude. TES arrays will open a new window for a higher sensitivity search for the proton or ion cyclotron features (or atomic lines from high Z elements) with a weak (shallow or narrow) line, and will be especially suited to studying bright burst spectra as well as monitor the evolution of magnetars' spectra.

If we turn our focus to accreting neutron stars, the highest-frequency quasi-periodic oscillations (QPOs) observed in accreting neutron star systems can provide unique constraints on the neutron stars themselves (Miller et al., 1998) if the oscillation can be associated with motion near the inner edge of the accretion disk. The current record is 4U 0614+09, which has a QPO with three-sigma lower limit on its frequency of 1267 Hz, yielding a constraint on the mass of this object of less than 2.1 $M_\odot$ (van Doesburgh et al., 2018). High-resolution spectroscopy of the QPO itself can bring the power of these constraints forward to obtain stellar mass measurements and probe the spacetime around the neutron star as well (perhaps measuring the moment of inertia). The objects that have been found to exhibit these high frequency QPOs are typically brighter than 0.1 Crab (this is in part a selection effect). They are sufficiently bright that a focusing instrument like the *X-IFU* on *ATHENA* (Barret et al., 2016) cannot perform spectroscopy due to photon pile-up, but a TES experiment with collecting optics could provide exciting measurements of neutron star masses and moments of inertia, as well as a basic test of the models for the QPOs.

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**1: How does the proposed initiative result in fundamental or transformational advances in our understanding of the Universe?**

The extreme nature of compact objects, in terms of gravity, density and magnetic fields, makes them particularly suited to advance our understanding of the behaviour of matter in extreme conditions. The study of reverberation mapping and QPOs will provide tests of general relativity in the strong field regime and simultaneously probes of the physics of accretion in the inner, hot regions close to neutron stars and black holes. Additionally, the observations of QPOs from neutron stars will help constrain the mass-radius relation of neutron stars. There have been hints of the presence of absorption lines in accreting and isolated neutron stars, which would provide information on the physical conditions on the neutron stars, including surface gravity, pressure, temperature and magnetic field. Future TES-based missions, like *Colibrì* or *ATHENA* will be able to robustly detect these features.

**2: What are the main scientific risks and how will they be mitigated?**

The X-ray observatories currently in space, such as *NuSTAR*, *XMM-Newton*, *NICER*, *SRG*, do not possess the combination of high spectral and timing resolution, throughput and sensitivity required by the science goals outlined in this paper, even if some preliminary reverberation mapping and QPOs observations in stellar mass black holes and neutron star have been undertaken at these observatories. The scientific rewards are unquestionable, however the main risk for the science goals would be the failure of currently planned or proposed missions (like *Colibrì* or *ATHENA*) to be approved and launched. The risk can be mitigated by a strong support and involvement by the community to push for currently planned and future X-ray missions.

**3: Is there the expectation of and capacity for Canadian scientific, technical or strategic leadership?**

The field of high-energy astrophysics (HEA) has experienced substantial growth in Canada over the past decade. Since the early 2000s, there have been over a dozen faculty hires (including into prestigious Chair positions), the formation of HEA research groups, and the contribution at a national level of hardware and expertise to the international X-ray missions *Hitomi* and *ASTROSAT*. The growth and activities have brought the Canadian HEA community to world-class levels, and its members are playing leadership roles in HEA efforts across the globe; a focus and push on X-ray science will position them naturally as leaders as TES-based observatories become a reality.

**4: Is there support from, involvement from, and coordination within the relevant Canadian community and more broadly?**

The authors of this paper comprise a large fraction of the Canadian HEA community. Moreover, the *Colibrì* team is collaborating with scientists in Europe and the US to enlarge and strengthen the science case.

**5: Will this program position Canadian astronomy for future opportunities and returns in 2020-2030 or beyond 2030?**

As mentioned several times throughout the paper, recent advancements in TES technology are at the base of a new class of X-ray observatories, characterized by unprecedentedly high spectral and timing resolution. The Hitomi and XRISM missions that have had Canadian involvement give a preview of this era of high-energy-resolution and high-sensitivity X-ray spectroscopy and timing. A middle-size mission has been proposed to the Canadian Space Agency by the authors of this paper, *Colibrì*, while a large-size mission, *ATHENA*, has been selected by the European Space Agency. By the early 30s, it is highly likely that a new TES-based mission will be in orbit. A focus on X-ray science, in particular on compact objects, will put Canadian astronomy at the forefront in this field.

**6: In what ways is the cost-benefit ratio, including existing investments and future operating costs, favourable?**

N/A

**7: What are the main programmatic risks and how will they be mitigated?**

N/A

**8: Does the proposed initiative offer specific tangible benefits to Canadians, including but not limited to interdisciplinary research, industry opportunities, HQP training, EDI, outreach or education?**

This initiative brings together researchers from across physics including general relativists, nuclear physicists, astrophysicists and condensed matter physicists. Building instruments or developing missions to study these questions will open opportunities for industry including particular Canadian companies and help develop a wide range of skills for future HQP.

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