Astro2020 APC White Paper

The *Colibrì* High-Resolution X-ray Telescope

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract:

We propose a high-time-resolution, high-spectral-resolution X-ray telescope that uses transition-edge sensors (TES) as detectors and collector optics to direct the X-rays onto the focal plane, providing a large effective area in a small satellite. The key science driver of the instrument is to study neutron stars and accreting black holes. The proposed instrument is built upon two technologies that are already at high TRL: TES X-ray detectors and collector optics.

1 Key Science Goals

In the past 50 years, we have been able to observe what could be defined as the most amazing laboratories in the Universe: black holes and neutron stars. These objects, often called compact objects, uniquely present an environment to test the laws of physics at their extremes: the 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. In this short period of time, we have learned a lot about compact objects, but their best kept secrets are still a mystery to us.

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 the spacetime around black holes well described by the Kerr metric?**
- ◇ **Can we better understand the physics of accretion? How do accretion disks lose angular momentum? What is the mechanism behind winds? How are jets launched?**
- ◇ **How does matter behave in extreme environments in terms of density, gravity and magnetic fields? What is the physics of ultra-dense matter? What are the masses and radii of neutron stars?**

This white paper presents a newly proposed mission, *Colibrì*, which will be able to investigate these questions to a new level, thanks to its unprecedented throughput and spectral and timing resolution in the 0.5-20 keV range.

Key science goals: Black Holes
Our science objectives include the study of accretion disk physics and the effects of strong-field gravity around black holes, as well as probing the spacetime around black holes and putting constraints on different theories of gravity. Specifically, we will achieve these objectives through the study of black hole reverberation and of quasi periodic oscillations in black-hole binaries [see also 1, (white paper 516)].

- Black hole reverberation:
  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 [2, 3]; the emission from a compact, optically thin corona above the black hole, which produces a power-law spectrum in the hard X-rays [4, 5]; 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 Kα fluorescence line at 6.4 keV and a reflection hump that peaks at $\sim$30 keV [6, 7].

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 [8], 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* [9, 10], and very recently in the X-ray binary MAXI J1820+070 with *NICER* [11].

The combination of high energy- and high time-resolution of *Colibrì* will allow us to detect these lags in the reverberation spectrum of X-ray binaries. High resolution spectral fitting of the X-ray emission, especially of the iron line profile, provides information on the effect of strong-field gravity on the orbiting plasma and its dynamics, yielding information about the orbital inclination, the black hole's spin, and the size of the accretion disk. The possibility of performing reverberation mapping, which yields distances in absolute units given by the light travel time, simultaneously with spectral fitting would therefore provide a test of the Kerr metric itself, as well as a measurement of the mass of the compact object [12–15]. 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.

- Quasi-periodic oscillations (QPOs):
  Nearly periodic fluctuations in the X-ray light curve, called quasi-periodic oscillations or QPOs, are commonly observed in accreting black hole and neutron star binaries [16–19]. They are usually divided in two categories: low frequency QPOs (LFQPOs), with frequencies $\sim 0.1 - 30$ Hz, and high frequency QPOs (HFQPOs), detected in the range $\sim 40 - 450$ Hz from black hole systems [20], and in the range $\sim 300 - 1200$ Hz (kHz QPOs) in neutron star systems [18, 21]. 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. LFQPOs were the first to be discovered, and several models have been proposed to explain their origin, from some instability in the accretion flow to a geometric oscillation [22–29]. The origin of HFQPOs 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 [30, 31, and references therein] and, for the case of neutron stars, beating with the neutron star spin frequency [32].

  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) [33, 34]. *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 exceptional 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 have much lower amplitudes than LFQPOs, and this explains 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.

Key science goals: Neutron Stars

We aim to study accreting and isolated neutron stars to understand the physics of accretion onto neutron stars and to measure the properties of neutron stars such as their mass, radius and atmospheric composition through high-time and high energy resolution spectroscopy [see also 35, (white paper 491)].

- Neutron-star accretion disks:

  Accretion onto neutron stars causes repeating thermonuclear reactions that are observed as bright bursts of X-ray emission, with timescales ranging from 100 ms to several hours [36–43]. Similar to the coronal emission for accreting black holes, X-ray-burst emission from the neutron star surface can be reflected by the accretion disk surrounding the neutron star, and indeed, reflection spectra have been observed [44–47]. A high resolution spectrum of the reflection emission can provide accurate measurement of the system's properties, such as the position of the inner radius of the accretion disk and the inclination angle of the system [48]. Moreover, the unprecedented combination of the large effective area and high timing and energy resolution of *Colibrì* will enable, for the first time, the detection of reverberation lags for neutron star X-ray binaries.

  The fastest variability components in X-ray binaries detected so far are kilohertz quasi periodic oscillations in neutron star binaries (kHz QPOs). They usually appear as a double peak in the power spectrum of the X-ray emission and the two peaks are observed to move up and down in frequency together in the 300-1200 Hz range. Similar to HFQPOs in black hole X-ray binaries, the higher-frequency peak of the kHz QPOs appears to be at frequencies comparable to the orbital motion close to the innermost radius of the accretion disk. The origin of the lower-frequency peak is still poorly understood, but it is thought to be somehow related to the spin frequency of the star [32]. If the higher-frequency peak is indeed caused by orbital motion, detection of kHz QPOs can put constraints on the mass-radius relation of the observed neutron star, simply due to the fact that the orbital motion has to happen both outside the star and outside the innermost radius of the accretion disk. The high timing resolution of *Colibrì* will allow additional detections of kHz QPOs, leading to stronger constraints on the mass-radius relation, and will enable better monitoring of high and low frequency QPOs, shedding light on the origin of the lower-frequency peak and on the correlation between kHz and low frequency QPOs.

- High-spectral-resolution, high-throughput spectroscopy of the neutron star surface:

  Neutron star photospheres are made of only the lighthest element present (most usually hydrogen), since the high surface gravity of neutron stars causes the elements in the atmospheres to stratify within 30 seconds. Accretion onto neutron stars is most usually expected to have occured (from a companion star, the interstellar medium, or fallback from the supernova). Therefore, hydrogen atmospheres with no absorption features in the X-rays are generally expected [e.g. 49]. Moderately high-resolution X-ray spectroscopy with *Chandra* and *XMM-Newton* has thus not revealed verified atomic absorption lines. Still, hints of the presence of absorption lines have been detected in accreting and isolated neutron stars alike, and the advent of high resolution spectroscopy in the X-rays could bring the detection of narrow and weak absorption features.

In actively accreting neutron stars, heavy elements might be present in the atmosphere, allowing the detection of absorption lines. Accreting material usually hides the surface of the neutron star, except during Type-I X-ray bursts and carbon superbursts. During these bursts, 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. [50] 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. It was further revealed that this particular source is rotating rapidly [51], which makes it challenging to explain the relatively narrow spectral features found [52, 53]. Since then, several X-ray bursts have shown evidence for broader features, likely due to heavy nuclear burning products being mixed up to the photosphere in particularly energetic bursts [54–56]. However, these observations were made with *RXTE*, with a spectral resolution insufficient to clearly identify the spectral feature. *Colibrì* will have the spectral resolution to clearly resolve edge features such as these, and the effective area to spot them in short time periods (~ 1 s), allowing robust determination of the surface redshift of these bursting neutron stars.

For neutron stars with rapid spins, spectral lines will be spread out by the Doppler shift; therefore, detecting and measuring the energy redshift 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. In general, these lines may be too broad to be detected if the neutron star is rotating very rapidly. However, some neutron stars are known to have relatively low spin (e.g. Terzan 5 X-2, [57]), and/or very low orbital inclination, either of which would narrow the lines sufficiently for possible detection [58]. The count rate during X-ray bursts will peak at about 5-10 kHz (scaling from *RXTE* results [42]) for *ATHENA* and *Colibrì*, which both plan to use TES X-ray detectors for spectroscopy. These particular observations would therefore be very hard for planned instruments such as the *X-IFU* on *ATHENA* [59], because of photon pile-up, but straightforward for *Colibrì*'s large effective area obtained by having many collectors operating in parallel, with each collector focusing X-rays on several elements of a TES array, and its nominal configuration can achieve high-resolution spectroscopy to count rates well beyond 10 kHz.

- High-spectral-resolution, high-time-resolution spectroscopy of the neutron star surface:

  Many accreting neutron stars are also rapidly rotating. The additional requirement of high-time-resolution to high-throughput emerges to observe phase-resolved spectral features. 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

[60], and if the emission pattern is known or can be constrained from observations, as it could be in Type-I X-ray burst oscillations [61],it becomes possible to constrain the mass and radius of the neutron star [62, 63]. The boost in effective area of *Colibrì* relative to *NICER* will allow us to study fainter objects on shorter timescales, and to derive constraints from ensembles of Type-I X-ray bursts with oscillations. The dramatic increase in energy resolution will make it possible to probe and constrain the underlying emission models, reducing potential systematic errors in the determinations of mass and radius.

Recently, the *Hitomi* satellite found strong evidence for weak and narrow absorption lines from the rotational-powered pulsar PSR J1833-1034 in the supernova remnant G21.5-0.9 [64] at 4.2345 keV and 9.296 keV. Depending on which line and on the configuration of the telescope, *Colibrì* would find two to ten times more photons within the line than *Hitomi*, with similar exposure time. Such an instrument would also open the possibility of phase-resolved spectroscopy to verify that the feature indeed originates from the pulsar rather than the supernova remnant. 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 [65] 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, while *Colibrì* would yield constraints more than ten times stronger for similar observing times.

Due to their high magnetic field ($10^{14} - 10^{15}$ G), magnetars are expected to have proton cyclotron lines falling in the X-ray band, and X-ray spectroscopy can provide a direct diagnostic of their total surface magnetic field strength. 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, 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 [66–68]. More recently, a variable absorption feature near 2 keV was discovered in a phase-resolved spectroscopy of the magnetar SGR 0418+5729 whose spin properties point to a much lower, below the QED value, magnetic field (6×10^{12} G), supporting high-order multipolar field components [69]. The line, 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. Observations of similar lines in more sources with higher sensitivity could reveal the structure of the magnetic field and the physics of magnetars. While early theoretical predictions suggest relatively wide absorption lines [e.g. 70, 71] 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 [72, 73]. This could reduce the line equivalent width by nearly an order of magnitude. *Colibrì* will enable 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 equipped to study bright burst spectra as well as to monitor the evolution of magnetars' spectra.

Table 1: Key Mission Parameters

Baseline requirements		**Optics**	
Energy range	0.5-20 keV	Focal length	4.9 m
Spectral resolution	2-5 eV	Number of Arrays	7
Timing resolution	250 ns	Foils per Array	30
Effective area	3,000 cm^2	Inner Radius	4 cm
Count rate	$>$100 kHz	Outer Radius	24 cm
Orbit		Geometry	Conical Wolter I
Altitude	1,688 km	Coating	Iridium
Inclination	103.0°	Field of View	50 arcseconds
Period	120 minutes	Angular Resolution	6 arcseconds
Sun Synchronous		**Detectors**	TES Bolometers
Payload		Bath Temperature	70 mK
Size	2.1 m x 7.0 m	T_c	100 mK
Mass	2,000 kg (fixed bench)	Array	12×12 (50 μm pitch)
Power	1,800 W	**Lifetime**	minimum 5 years

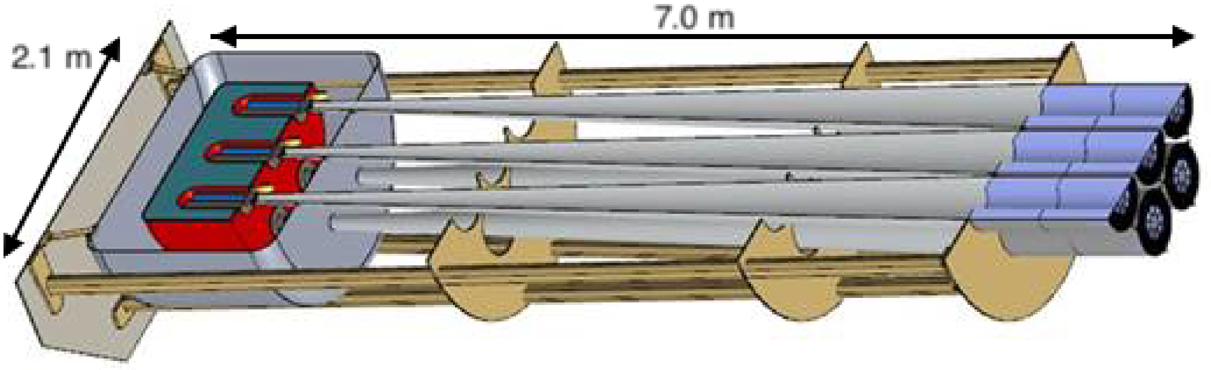

Figure 1: Cut-Away of *Colibrì* to highlight the optical path, detectors and cooling concept.

2 Technical Overview

The key characteristics of *Colibrì* are its high spectral resolution, high throughput and large effective area, and they can all be achieved by using already mature technologies: thin-foil nested X-ray mirrors and transition-edge sensors as single-photon X-ray bolometers. Please consult Tab. 1 for an overview of the mission parameters. An array of seven telescopes yields a total effective area slightly larger than the three *XMM-Newton* telescopes with a focal length of 4.9-metres (see Fig. 1). The reduced focal length is achieved by reducing the outer diameter of each telescope to 32 cm (compared to the 70 cm for *XMM-Newton*) and by optimizing the on-axis performance at the expense of performance off-axis. This results in a large effective area for high-resolution spectroscopy from 0.2 keV to 20 keV as shown in Fig. 2 *Colibrì* offers a similar energy resolution to the gratings on Chandra and *XMM-Newton* and to the bolometers on *Hitomi* SXS, but with ten times the effective area of these missions. It gives a similar energy resolution to *ATHENA* with lower effective area below about 6 keV, but higher above 6 keV, because of the mirror-design

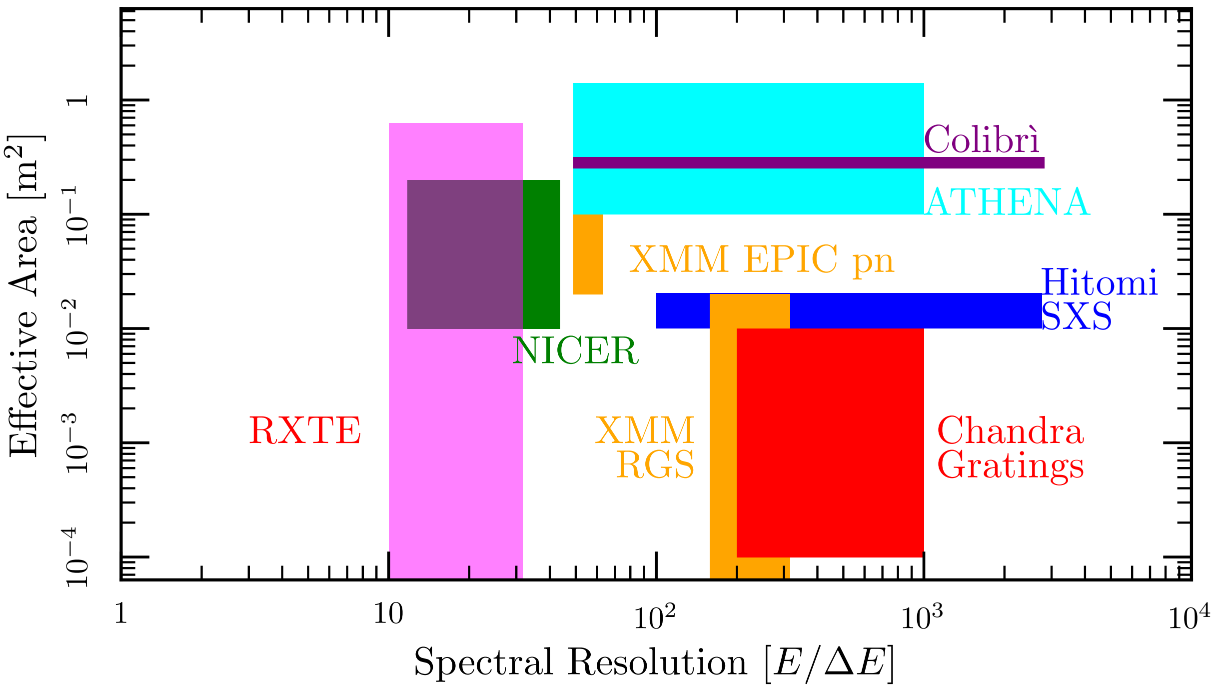

Figure 2: X-ray Missions with X-Ray Spectroscopy Figures of Merit: Effective area and Spectral resolution at 1 keV and 10 keV

choices.

The second key characteristic of *Colibrì* is high throughput combined with high-time resolution. The optics are purposefully defocused so that the emission from a source on axis is spread over a large portion of a TES array. Furthermore, seven arrays operate in parallel. This dramatically reduces the likelihood of several photons landing on the same detector element within a short time, which would result in poor energy measurements, pile-up and lost photons, and allows to sustain count rates a factor of 1,000 larger than *ATHENA*. Furthermore, because the individual detector elements relax more quickly than those planned for *ATHENA*, and there are seven arrays operating in parallel, *Colibrì* will over-perform *ATHENA* by more than a factor of ten in count rate even if *ATHENA* offers a defocused observing mode. *Colibrì*'s rapid sampling of the TES arrays will achieve a time resolution similar to that of *NICER* and a factor of one-hundred finer than *ATHENA*. Fig. 3 depicts a summary of past, current and planned missions in the X-ray-timing space.

3 Technology Drivers

At its heart, *Colibrì* relies on TES-enabled X-ray bolometers with small relaxation times and high sampling rates. These detectors, combined with non-focusing optics, yield high throughput, high spectral and timing resolution and high quantum efficiency over a wide range of photon energies. The performance that is required for *Colibrì*'s bolometers has already been achieved in the laboratory, and similar detectors are already in use at X-ray beamlines. *Colibrì* could be the first

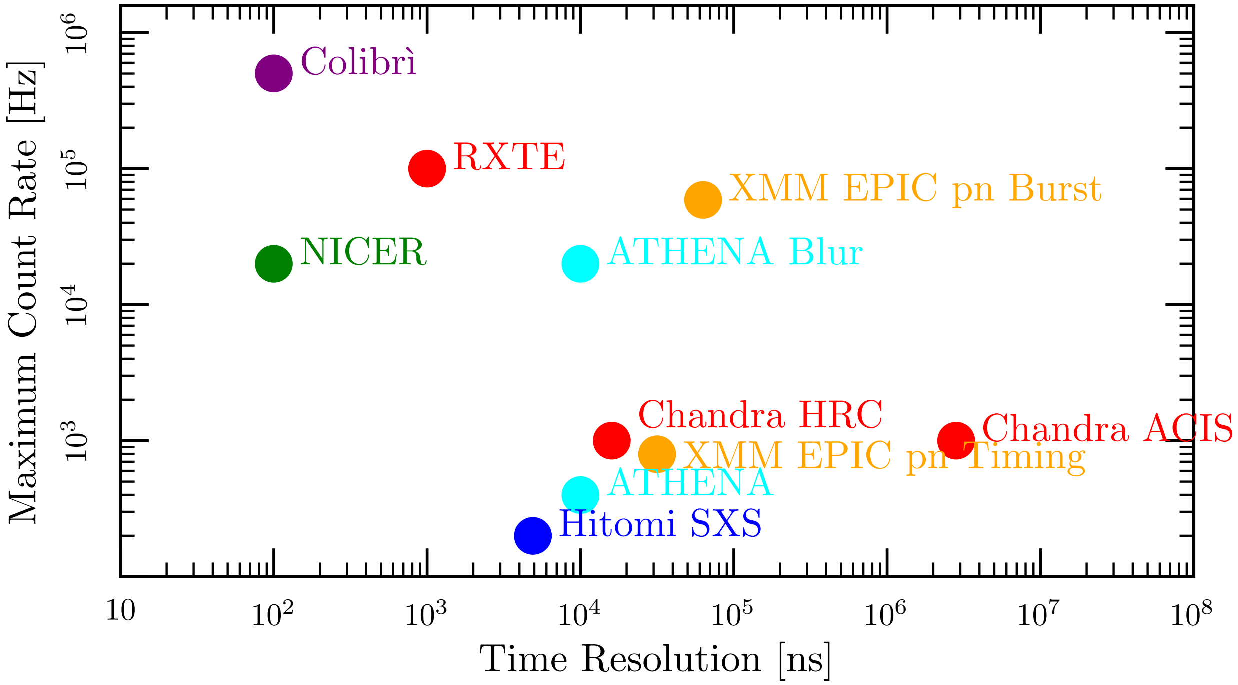

Figure 3: X-ray Missions with X-Ray timing figures of merit: time resolution and throughput

mission to use these detectors in space. Although *Colibrì* requires a cryogenic focal plane, the individual detector arrays and the accompanying superconducting electronics are much smaller than the focal planes of recent CMB experiments (e.g. Planck HFI at 100 mK) that have required similar operating temperatures; *Hitomi*'s SXS used a similar technology as *Colibrì*, and operated also at 50-100 mK. Furthermore the X-ray optics are well tested; telescopes with similar or better performances have been used on many missions.

The first key technology challenge is the on-board pulse processing that is required to achieve the energy and time resolution. Each of nearly two thousand TES bolometers must be sampled every 5 microseconds, for a total sampling rate of 400 MHz. We have developed a scheme of linear filters to achieve the required energy and time-resolution that will limit the required on-board computation to a manageable level. For example, *Hitomi*'s SXS pulse processor was limited to count rates below 200 Hz by computational constraints. We plan to achieve counts of 100s of kHz from sources with Crab-like fluxes.

The second key challenge is to bring the data back to the ground. During a day-long observation of a bright source, *Colibrì* will amass about 50 GB of data (assuming just five bytes per photon), twenty times the mean rate for HST and one-fifth that of JWST. However, with *Colibrì* in low-Earth orbit, the time each day to downlink data to a single ground station is dramatically diminished. We are exploring three options: a high-frequency (e.g. Ka-band as for JWST) downlink to a single ground station, downlink via satellites in high Earth orbit (as for Hubble) and an optical downlink to a telescope ground station. The final option potentially offers the most flexibility and room for growth but also is the most technically challenging.

The total power requirement for cooling the focal plane is about 1600 Watts. Although we do not yet have power estimates for other systems, cooling will play a major part of the power budget

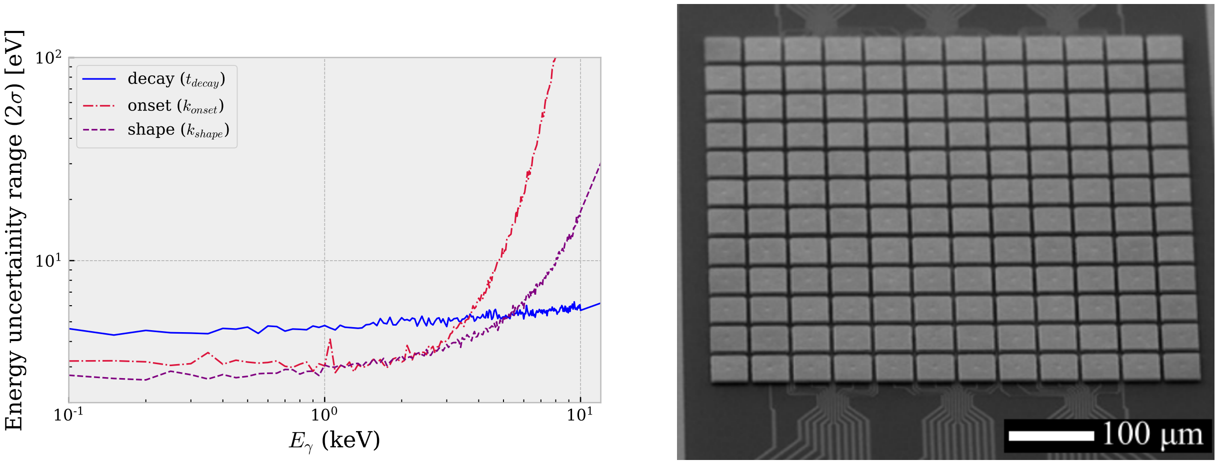

Figure 4: Left: Energy resolution achieved with linear filters, 5.12 μs sampling, thermometer and Johnson–Nyquist noise. Right: TES array for X-ray detection from [74]. The collector optics focus X-rays to a spot on the order of one millimeter in extent, hence the TES array will highly oversample the PSF to achieve high throughput.

for the mission.

4 Organization, Partnerships, and Current Status

The *Colibrì* collaboration consists of most of the Canadian high-energy astrophysics community teamed up with Canadian particle and condensed matter physicists as well as other scientists around the world. We are in the midst of an 18-month science concept study funded by the Canadian Space Agency, with Honeywell and MDA as industrial partners. The preliminary optical design and cooling concept are complete. The focus of the second half of the study is the further development of the science case and a detailed plan for the payload and spacecraft bus. The study will end in early 2020. We have identified several additional potential partners: NASA (mirrors and TES detectors), NIST (TES detectors) and the Canadian Light Source (testing and calibration), NASA/ESA (launch).

5 Schedule

The proposed *Colibrì* mission is currently in a science concept study stage, to be concluded in early 2020. This stage will define the mission success criteria as well as the mission requirements. In an optimistic timeline, the mission definition phase will continue for 4 years. During this time, science maturation studies and technology development studies will proceed in parallel to the mission definition in order to increase the science and technology readiness levels.

Over the subsequent 6 years, activities leading to launch will include defining the system requirements, a preliminary system design and a detailed system design, and then fabricating, integrating and testing the system. A data analysis pipeline will also be developed. This will lead to a mission launch in about 10 years, in the early 2030s. After the commissioning activities, the nominal science operations are estimated to occur over 5 years. Decommissioning activities are estimated to take 2 additional years (ending in 2037) with the safe disposal of the *Colibrì* space mission and final data archiving with documentation to ensure the usefulness of *Colibrì* data long after the mission is completed.

6 Cost Estimates

We are currently performing the science concept study for the *Colibrì* mission, so we do not have cost detailed estimates; however, we argue that *Colibrì* would fall into the small mission category with a cost of less than $500M.

Acknowledgements

The authors would like to acknowledge support from the Canadian Space Agency, the Natural Sciences and Engineering Research Council of Canada, the Canada Foundation for Innovation and Compute Canada.

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

2: Are the associated scientific risks understood and acceptable?

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

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

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

6: Is the cost-benefit ratio, including existing investments and future operating costs, favourable?

7: Are the main programmatic risks understood and acceptable?

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?

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