The Extreme Physics Explorer

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ABSTRACT

Some tests of fundamental physics - the equation of state at supra-nuclear densities, the metric in strong gravity, the effect of magnetic fields above the quantum critical value - can only be measured using compact astrophysical objects: neutron stars and black holes. The Extreme Physics Explorer is a modest sized (∼500 kg) mission that would carry a high resolution ($R \sim 300$) X-ray spectrometer and a sensitive X-ray polarimeter, both with high time resolution ($\sim 5\ \mu$s) capability, at the focus of a large area (∼5 sq.m), low resolution (HPD∼1 arcmin) X-ray mirror. This instrumentation would enable new classes of tests of fundamental physics using neutron stars and black holes as cosmic laboratories.

Keywords: X-ray optics, spectroscopy, polarimetry, timing, neutron stars, black holes, magnetars, fundamental physics

1. INTRODUCTION

All scientific fields go through three phases: *discovery*, *understanding*, and *tool.* In the *discovery* phase there is widespread excitement over the new field and prizes are won as the basic properties of the field are explored; in the *understanding* phase interest narrows to those specialists willing to commit to the intensive research that leads to physical understanding; at some point though the remaining problems become so small that the field becomes boring; not until the experts have achieved that understanding does the field become of wide interest again, but this time as a *tool* to unlock other fields of study.

X-ray astronomy is now over 40 years old and the first area of study within X-ray astronomy - the neutron star and black hole X-ray binaries - have long been in the *understanding* phase, and interest in the field has shrunk to a relatively small expert group. The progress made by this group however, largely thanks to the *Rossi X-ray Timing Explorer* (Swank 1998), has been impressive, so that many of the key astrophysical properties of these exotic systems have been pinned down. This progress has paved the way for the opening of the third phase: the use of compact X-ray binaries as a *tool* to explore the *extreme physics* for which neutron stars and black holes are natural laboratories.

Here I propose the *Extreme Physics Explorer*, a moderate cost, moderate risk, mission to allow precision measurements of the fundamental physics that is only probed with these exotic objects.

2. EXTREME PHYSICS

It is well known that astrophysics provides many environments far more extreme than can be created in laboratories on Earth. The early universe is the best known case, and the discovery of Dark Energy (Riess et al., 1998, Perlmutter et al., 1998) and the possibility of exploring the nature of inflation via polarization signatures in the Cosmic Microwave Background (Seljak & Zaldarriaga 1997, Kamionkowski et al., 1997) are exciting and vibrant fields of study.

The physics found in the extreme conditions of density found in neutron stars, of strong gravity around black holes, and of quantum critical magnetic fields in the magnetar class of neutron stars, while studied, is not so dynamic a field. (The properties of each class of object are described briefly below.) The reason for this lack of dynamism is twofold: the emergence only recently of a good physical understanding of much of the gas dynamics within these systems (the astrophysics), which obscures the fundamental physics, and the lack of precision tools

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with which to probe this physics. Most proposed physics tests using these objects employ *timing* (Kouveliotou et al., 1999, Heyl & Hernquist 2003, DeDeo & Psaltis 2004), but the diagnostic potential of *high resolution spectroscopy*, though less explored, is far greater. A combination of *time resolved spectroscopy* would be most powerful of all. A fascinating set of proposed physics tests use the *polarization* of the X-ray radiation, e.g. as a test of the black hole metric (§2.2).

Both spectroscopy and polarization are less developed because both are photon-hungry applications, making sufficiently sensitive observations appear to be out of reach. The *Extreme Physics Explorer* makes these tests practical.

2.1. 'Neutron' Stars

Neutron stars are particularly promising objects with which to study extreme physics as they:

1. probe regions of space-time curvature orders of magnitude more curved than e.g. the Hulse-Taylor pulsar (de Deo & Psaltis, 2003);
2. are strong X-ray sources (10^3counts $s^{-1}m^{-2}$ for objects in our Galaxy), when in compact binary systems;
3. have a hard surface, enabling precision measurements;
4. rotate rapidly (P=1 msec - 1 minute), providing a reliable pulsed signal that enables time-dependent features to be resolved;
5. have a thin (∼1 cm scale height) atmosphere, which imprints narrow atomic features in their spectra;

All of these features combine to make them, in principle, excellent 'accelerators' with which to perform extreme physics experiments via timing and spectroscopy.

2.1.1. 'Neutron' Star Equation of State

Neutron stars are not likely to be made simply of neutrons at their cores. Instead a variety of different particle compositions, all the way down to the densest 'quark' stars have been proposed (Lattimer & Prakash 2001). The way to distinguish these models, and so learn the behavior of matter at extreme densities is via the equation of state of neutron stars - i.e. their pressure-density relation. Although this is a fifty year old question, this equation of state is at present unknown. The reason is that the relation depends on physics that cannot be tested in the laboratory (Miller 2003). If the Mass-Radius relation of 'neutron' stars could be measured, this would determine their equation of state. However, although orbital solutions for X-ray binaries can measure the mass of the 'neutron' star, they do not measure its radius.

The discovery by Cottam, Paerels & Mendez (2002) using the Reflection Grating Spectrometer (RGS, den Herder et al., 2001) on XMM-*Newton* (Jansen et al., 2001) of a redshifted system of absorption lines (Fe XXVI and Fe XXV 2-3, and OVII Lyα) in the X-ray spectrum of the binary EXO 0748-676 makes a strong case for a gravitational origin of the redshift. With a value of 0.35 ± 0.04 the redshift is consistent with neutron stars made of normal nuclear matter, and excludes some more exotic states of matter such as strange quark matter or kaon condenstates.

This is a breakthrough result in several ways: first it shows that neutron star atmospheres, under some conditions, contain sharp spectral signatures; second it shows that the redshift gives an M/R value in the expected range, meaning that the origin is likely gravitational. Cottam et al. thus opens up the whole field of precision measurements of neutron stars.

However, the Cottam et al. result, unsurprisingly for a first measurement, is limited in several ways:

1. The redshift has 10% errors. This is not a limitation of the RGS, which has a spectral resolution $\lambda/\Delta\lambda$ = 400. Hoogerwerf et al. (2004) have made a measurement with the *Chandra* LETGS, which has similar spectral resolution, accurate to ±4 km s^{-1} (albeit for a relative velocity rather than an absolute one). Rather it is a limitation of counting statistics.

2. The measurement was integrated over 28 bursts from EXO 0748-676. Any changes in the emitting region from burst to burst, or around the 3.82 hr orbital period, could weaken and smear out the signal.
3. The observation was limited to the 3 s time resolution imposed by the readout of the CCD detectors of the RGS. All phase resolved information about the absorption lines is thus lost.

To measure M/R$\sim$0.3 to 1% implies a spectral resolution, $\lambda/\Delta\lambda$, $\sim$300, which is ΔE=20 eV at 6 keV and ΔE=3 eV at 1 keV. The Cottam et al. result used lines close to 1 keV, so 3 eV is a good fiducial ΔE for any follow-up spectroscopy.

Time resolved spectroscopy enables an entirely new constraint on the neutron star radius. The Doppler shift of the absorption line changes as it rotates around the neutron star, assuming that the ionized gas in the atmosphere is localized rather than uniformly spread. For a 10 km radius and a 10 ms period this velocity would be of order $\pm$6 km s^{-1}. This would be a relative measurement and at the level of precision attained by Hoogerwerf et al. would already yield a 3σ detection. With excellent statistics and careful calibration a precision amplitude could be measured. Then, combined with a spin period for the neutron star known from light pulsations, the radius is determined, modulo only the unknown *sin i* due to the inclination of the neutron star rotation to our line of sight (but see §2.3).

2.2. Black Holes

The X-ray emission from black hole binary systems and active galaxies originates close to the event horizon. Evidence for a strongly gravitationally redshifted emission line due to the 6.4 keV neutral Fe-K transition has been reported in both types of system (Tanaka et al., 1994, Wilms et al., 2001, Miller et al., 2002, Tiengo et al., 2005). In principle these lines can be used to probe the metric at the strongest curvatures, next to the event horizon (Reynolds et al., 2005).

These observations, though, are at the limit of count rate and spectral resolution of current instruments, leading to tantalizing results. The variability properties of the broad redshifted component of the Fe-K line are puzzling, but one explanation would put the emission at just 2 Schwartzschild radii (Fabian 2005). Rapid variability of narrow features within this broad line wing may be signaling orbiting hot-spots with coherence times of a few orbits (Turner et al., 2006). *Extreme Physics Explorer* spectra would have the signal-to-noise, spectral resolution and bandwidth to turn these edge-of-detectability results into tools.

Polarimetry offers another way to probe the warped metric near a black hole. As different energy radiation is believed to originate from different radii, the effects of GR warping of the light will be energy dependent, and the size of the effect can determine the black hole spin (Stark & Connors, Connors & Stark 1977, Connors, Piran & Stark 1980 ApJ, 235, 224). Moreover the polarization angle of the radiation determines the orientation of the accretion disk on the sky (Sunyaev & Titarchuk 1985). Since the black hole mass is known from binary orbit analysis (or from reverberation mapping for AGNs), all of the black hole parameters (except charge) are will then be determined.

The combination of spectroscopy and polarimetry over-determine the black hole properties and so allow tests of GR in the strong gravity regime.

2.3. Magnetars

The 'magnetars' are a small subset of neutron star binaries containing highly magnetized neutron stars. In these systems the magnetic field is above the quantum critical limit $B_c = 2\pi m_e^2 c^3/he = 4.4\times10^{13}$ gauss, reaching much higher values up to 10^{15} g (Thompson & Duncan 1995, 1996). At these field strengths interesting new effects are predicted (Erber 1966, see e.g. Miller 2001 for a recent review). For example, the transmission of light through a super-critical field is polarization dependent (e.g. Broderick & Blandford 2003), and a characteristic polarization signal is expected. This technique can also determine the orientation of the neutron star rotation axis on the sky (Meszaros et al., 1988), so removing one of last astrophysical unknowns from the problem.

A spectroscopic example is that, at super-critical field strengths, the cyclotron radius is smaller than the Bohr radius. As a result there is a squeezing of the wave packet along the field lines. This squeezing shifts the atomic energy levels, leading to e.g. hydrogen Lyman-α being shifted up into the soft X-ray regime (Ho et al., 2003).

2.4. Astrophysics

Although the *Extreme Physics Explorer* is designed as a physics experiment, it will also be powerful as an observatory for a wide range of astrophysics, and we list a few examples here:

Spectroscopy:

- 'occultation' experiments via rapid variability of absorbers in AGNs (Risaliti et al., 2006);
- AGN wind location and characterization using non-equilibrium modelling of 'Warm Absorbers' (Krongold et al., 2006);
- spectral Doppler mapping of the nearest several supernova remnants, galaxies and clusters of galaxies;
- thermonuclear burning in X-ray bursts;
- element abundances in star formation regions;
- stellar coronal dynamics;
- charge exchange spectra of comets;

Polarization:

- reflection spectra of hidden AGNs;
- emission from white dwarf binaries (CVs);
- accretion disk atmosphere scattering;
- diagnostics of jets in quasars and microquasars;
- scattered light in clusters of galaxies (Churazov 2003).

3. THE *EXTREME PHYSICS EXPLORER*

To overcome the limitations of current, and currently planned, observations requires instrumentation with much larger area, much improved time resolution and at least comparable spectral resolution to those now flying. An advance of this magnitude is possible using microcalorimeters as high time resolution spectrometers, combined with existing extremely light-weight X-ray optics to give large collecting areas. The area needed is of order a few square meters: each observation needs 10^8 counts, while most X-ray binaries count at 10^3ct $s^{-1}m^{-2}$; a measurement needs to take place in a time small compared to an orbital period, or to changes in the astrophysical gas flow, i.e. hours or less. Such large areas preclude the use of dispersive spectroscopy (gratings), as these need good optics (HPD $<$ 10 arcsec).

The essential realization behind the *Extreme Physics Explorer* is to note that, in this special application, 'bad imaging is good'; that is a diffuse point spread function (PSF) can be used to spread the signal over an 1000 pixel microcalorimeter array, enabling the array as a whole to count at 1 MHz, as needed.

3.1. Microcalorimeters

Microcalorimeters are not usually thought of as good timing devices. Yet the rise time of the pulse created by an individual photon in a microcalorimeter is only ∼50 μs, so that the pulse peak can be timed to ∼5 μs. Since microcalorimeters are now approaching an energy resolution, ΔE∼2 eV, and have essentially unit quantum efficiency down to at least 0.5 keV, they would appear to be ideal detectors for the study of physics using compact objects.

Their limitation is that the decay time of the pulse is much longer, ∼300 μsec (e.g. Ohno et al., 2002). Hence pulses arriving at rates greater than ∼1 kHz will pile-up on one another and the energy resolution of the detector will be degraded. Con-X will suffer from this limitation. 1000 ct s^{-1} is too low a rate to allow interesting timing analysis.

Fortunately, this is a *per pixel* count rate limit. A uniformly illuminated 32×32 microcalorimeter array could count at 1 MHz, a rate adequate to gather the needed signal in the requisite time. However, microcalorimeter arrays are small, ∼1 cm^2, and need to be cooled to ∼70 mK, so that scaling up to square meter areas is unrealistic. Clearly the microcalorimeter array needs to be fed by a large, though not exquisite, X-ray optic.

As shown in section 3.3, the *Extreme Physics Explorer* will have a plate scale of 1.5 cm/arcmin, so that a pixel size of ∼500 μm (2 arcsec) is needed to get the required per pixel count rate. 500 μm pixels are double the dimension of those planned for Con-X (Kilbourne et al., 2005) and the same as those for DIOS (Ohashi et al., 2006). So this is a good match of requirements to technology.

To achieve ΔE = 3 eV needs a small heat capacity in the pixel. Compared to Con-X, a thinner converter could be used. This would lower the heat capacity, as needed, but would also lower the quantum efficiency of the array at high energies. A solution to this involving a 'beam splitter' is described below (§3.3).

The minimum required array size is 32×32, but this allows for no jitter in the image location on the detector, and so would lead to unreasonably tight tolerances on the aspect solution and the mirror-detector alignment. A 42×42 array would allow for 5 arcsec rms image jitter which is a more realistic minimum requirement. A 64×64 array would leave much more leeway for the rest of the system, but is just beyond current fabrication capabilities. The trade between array size and optical bench tolerances is non-obvious and will need study.

3.2. Polarimeters

The polarization of cosmic X-ray sources is a poorly developed field. Only the Crab Nebula has a detected polarization signal (Weiskopf et al., 1978). The underlying cause for this lack of development is the photon-hungry nature of polarimetry: four Stokes parameters need to be determined, and to detect a 1% polarization signal at 10 σ requires 10^6 photons. This calculation assumes 100% modulation of the signal, which is never achieved in real devices. The 'minimum detectable fractional polarization' (at 99% confidence), $M = \frac{4.29}{\mu S}\sqrt{\frac{(S+B)}{t}}$, where S is the source count rate, B the background count rate, t the observing time, and μ the modulation factor. *Extreme Physics Explorer* provides large S and small B. The crucial remaining parameter is μ, which must be close to unity, but has not been the case for polarimeters in the past.

The potential for X-ray polarimetry is, however, large. This was demonstrated by the 2004 'X-ray Polarimetry Workshop' at the Kavli Institute for Particle Astrophysics and Cosmology*. Many applications of X-ray polarimetry were discussed, and a number of novel techniques for detecting polarization were presented at this meeting.

One of the most promising polarimeter developments for the standard energy range of grazing incidence optics (0.1-10 keV), is that of the 'Micro Pattern Gas Polarimeter' (Costa et al., 2001). This device has several characteristics that are well suited to the Extreme Physics Explorer. In this device polarization information is derived from the tracks of the photelectron, which are imaged using a finely subdivided gas detector ('PIXI', Costa et al., 2006). The tracks are long enough that a 50% modulation factor has been achieved at 5.4 keV. The third generation device now being tested is 1.5 cm diameter, well matched to the PSF of the *Extreme Physics Explorer*. The individual triggering of the 10^6 pixels in this device enables the 3 - 10 μs time resolution appropriate for *Extreme Physics Explorer*. The Micro Pattern Gas Polarimeter has the moderate energy resolution typical

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*URL: http://www-conf.slac.stanford.edu/xray_polar/Talks.htm of other gas counters, and operates at around room temperature. Being a gas counter the instrument could not operate at the cryogenic temperatures of a microcalorimeter, as the gas would liquefy. Use of this device would thus require dividing the focal plane into cold and warm sections. A compact cryostat (e.g. a 50 cm on a side cube, as on DIOS, Ohashi et al., 2006), and the inherently wide field opticcs of conical optics (§3.3), would allow the two instruments to share the focal plane. Offset pointing would be used to select which one recieves the target's photons.

3.3. Microchannel Plate Optics

Microchannel plate optics (Beijersbergen et al., 1999) have the right properties to create the low resolution mirror that feeds the instruments on the *Extreme Physics Explorer* †:

1. weight 3.7 kg m^{-2}: c.f. 250 kg m^{-2} for the Con-X optics;
2. sub-arcminute PSF: demonstrated by Bavdaz et al. (2002);
3. high aperture utilization, with good reflectivity up to high energies;
4. plate-like thin, rigid structures: can fold and deploy readily, like solar panels;
5. large field of view: inherent in the conical approximation to Wolter I optics (Petre & Serlemitsos 1985).

These optics have been developed extensively by the University of Leicester and ESA's ESTEC center, for use in the LOBSTER all sky monitor program (Fraser, G. & Bannister, N., 2002), based on an original concept by Roger Angel (1979). An arcminute PSF spreads out the signal over many pixels, as needed for the *Extreme Physics Explorer.* It may be possible to optimize the PSF further toward the ideal of uniform illumination, by introducing small deliberate alignment offsets individual small plates in the mirror. The tolerances required to produce a 'top hat' beam profile need investigation.

While an arcminute-scale PSF is by no means high resolution, and in fact performs the valuable function of spreading out the signal on the microcalorimeter array, it is not so bad, being similar to that of ASCA (Tanaka et al., 1994). The *Extreme Physics Explorer* would resolve the 'nest of black holes' toward the Galactic Center (though not the central black hole X-ray source Sgr A*), and would be capable of reaching the brightest few dozen Active Galaxies (AGNs) and quasars without being excessively background limited. (The use of active anti-coincidence shields around the microcalorimeter on *Suzaku* led to lower backgrounds than in the ASCA CCDs, Kilbourne et al., 2006.) A few additional pixels unexposed to the incoming X-ray beam could serve as a recorder of the remaining background. Background is unimportant for Galactic X-ray binary observations.

To reach a collecting area of several square meters requires a ∼5 m diameter mirror. This might be achieved with a set of seven 1.7 m diameter mirror panels that deploy in orbit. To preserve the small, grazing incidence, angles needed for X-ray reflection, an long focal length, ∼40 m, is required. At 40 m a 1 arcmin spot has a size of 1.5 cm. This is a good match to microcalorimeter arrays. The 40 m long focal length is much less of a difficulty than might be imagined (see next section), and is eased by the cm-sized spot created by the microchannel plate optics, as this leads to relatively loose tolerances for maintaining the relative mirror-detector location.

Microchannel plate optics have good high energy reflectivity, so it would be wasteful not to detect these photons efficiently, not least because the 6.4 keV Fe-K line is an important diagnostic around black holes. Yet to attain $\Delta E = 3$ eV at 1 keV, the microcalorimeter array may have to compromise high energy quantum efficiency. An ideal arrangement would be to have a beam splitter to divide the incoming X-ray beam by energy at ∼2 keV. The two beams could then be directed to separate microcalorimeter arrays optimized for the two bands.

I propose here a novel way of creating an X-ray beam splitter: by having the outer parts of the second reflector - which have larger graze angles and reflect lower energy X-rays - canted by a few (∼5) arcminutes from optical axis of the inner parts of the mirror. (Normally one would talk of the outer and inner shells, but microchannel plate optics do not have simple shells.) This small tilt is only 10% of the graze angle, so will have minimal effect

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† Note that these are *not* the same technology as the micropore silicon optics being developed for XEUS (Collon et al., 2006) which are heavier, but have much higher resolution.

Table 1. Mass Budget

Item	Mass (kg)
10 m^2 microchannel plate mirror	37
Mirror support assembly	37
Optical bench, extending to 40 m	20
Calorimeter & Cryostat*	123
Spacecraft	200
20% reserve	83
Total	**500**

* Based on ASCA design.

on the reflectivity, while the PSF is dominated by alignment effects and will not be affected by this small off-axis deviation. A side benefit of separated high and low energy response is a doubling of the maximum mission count rate. If the tilt is chosen so that the two PSFs overlap slightly then a small fraction of the low energy beam will fall on the high energy detector, and vice versa. This will enable good cross-calibration of the two arrays, as will the overlap in their effective area vs. energy curves.

3.4. Spacecraft

Clearly a 40 meter focal length requires an extending optical bench. (Launcher farings do not exceed lengths of a few meters.) The alternative of a pair of separate, independently free-flying, mirror and detector spacecraft, as planned for *Simbol-X* (Ferrando et al., 2005) adds major complications, especially in a low earth orbit where gravity gradients are strong.

A minimum factor of ∼10 extension is needed for the optical bench. Fortunately, a light-weight deployable optical bench exists and has been flight-tested on numerous missions: UARS, GGC WIND, GGS POLAR, Cassini, Lunar Prospector, IMAGE (Able Engineering: URL http://www.aec-able.com/Booms/ablebooms.html, http://www.aec-able.com/ableflightherita.html). Most of these were relatively short booms, but the longest reached ∼20 meters. An extension to 40 meters should not be problematic.

Thanks primarily to the lightweight optics and optical bench, the total mass of the *Extreme Physics Explorer* is modest, ∼500 kg. Table 1 gives a preliminary breakdown of the mass budget. The calorimeter/Cryostat mass may be reduced somewhat if a DIOS-like design (100 kg, Ohashi et al., 2006) is adopted. A modest additional mass for the polarimeter instrument needs to be calculated and included.

The operations of the *Extreme Physics Explorer* are expected to consist primarily of ∼day-long pointings at bright (10^3 ct s^{-1} m^{-2}) Galactic X-ray binaries. A long (>5 year) mission is feasible if a cryogen-free cryostat can be employed (e.g. the 5-stage system proposed for DIOS, Ohashi et al., 2006). Rapid slews to ToOs are implausible with a 40 m long spacecraft. A small 'all sky monitor' (e.g. ASPEX, Feroci et al., 2006), to alert mission controllers to transient X-ray sources, would be a useful addition to the mission, as these sources remain bright for days to weeks, and track through a range of accretion rates, some of which are more optimal than others for physics experiments.

The low mass of the *Extreme Physics Explorer* leaves adequate launch capability to reach a high orbit. A high orbit would enable continuous viewing of these targets which: (1) simplifies Fourier analysis of their properties, (2) ensures full coverage of orbital phases, (3) doubles the observing efficiency, compared with LEO, (4) reduces gravity gradient torques, simplifying the attitude control system; and (5) reduces the heat load on the cryostat.

This observing profile implies continuous event rates of 10^4 ct s^{-1}. Each microcalorimeter event will need 10 energy bits (2 eV in 2 keV), 20 timing bits (5 μs in 5 s), and 10 pixel ID bits, which sum to: $4{\times}10^5$ baud. Including aspect and housekeeping a continuous data rate of 0.5 MB is needed. Ground contact will need to be extensive. Perhaps even a GEO orbit should be considered because of the continuous coverage it affords, despite the high backgrounds encountered there.

4. MAIN CHALLENGES

For convenience we summarize the main challenges to realizing the *Extreme Physics Explorer*:

- Microcalorimeter arrays with <3 eV resolution and at least 42×42 format (64×64 preferred), and the multiplex readout electronics to support them;
- Mass manufacture of microchannel plate optics, and their alignment;
- Deployment of MCP optics and optical bench, and maintenance of alignment;
- Size of cryostat (to allow polarimeter close to optical axis);
- High data rate (background in GEO?);
- Refinement of science case.

This last item, the refinement of the science case, is pressing as it may alter the mission architecture. The full range of potential physics tests has surely not been exhausted in the literature. The science case needs to be carried through to full simulations of observations of specific X-ray binaries. Targeted workshops to develop the science case for the *Extreme Physics Explorer* would be valuable.

5. CONCLUSIONS

The *Extreme Physics Explorer* is a modest sized (∼500 kg) mission that would carry an X-ray spectrometer and an X-ray polarimeter, both with high time resolution (∼5 μs), at the focus of a large area (∼5 sq.m), low resolution (HPD∼1 arcmin) X-ray mirror.

This instrumentation would enable a new class of tests of fundamental physics using neutron stars and black holes as cosmic laboratories.

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