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Epoch of Reionization Energetic X-ray Survey (EREXS)
to measure the birth and growth of the first Black Holes

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Abstract

The Epoch of Reionization Energetic X-ray Survey (*EREXS*) is designed to i) use the birth of stellar mass black holes, as revealed by cosmic Gamma-Ray Bursts (GRBs), as probes of the first stars and galaxies to exist in the Universe. Both their extreme luminosity (~10^4 times larger than the most luminous quasars) and their hard X-ray detectability over the full sky with wide-field imaging make them ideal "back-lights" to measure cosmic structure with X-ray and near-IR (nIR) spectra over many sight lines to high redshift. The full-sky imaging detection and rapid followup narrow-field imaging and spectroscopy allow two additional primary science objectives: ii) novel surveys of supermassive black holes (SMBHs) accreting as very luminous but rare quasars, which can trace the birth and growth of the first SMBHs as well as quiescent SMBHs (non-accreting) which reveal their presence by X-ray flares from the tidal disruption of passing field stars; and iii) a multiwavelength Time Domain Astrophysics (TDA) survey to measure the temporal variability and physics of a wide range of objects, from birth to death of stars and from the thermal to non-thermal Universe. These science objectives are achieved with the telescopes and mission as proposed for *EREXS* described here.

1. INTRODUCTION

Black holes, with masses ranging from stellar to supermassive (~$10^{0.5\text{-}10}$ $M_\odot$), are now recognized as fundamental to the very formation of galaxies and, by extension, their constituent stars, planets and perhaps (even) life. Although it is only the supermassive black holes (SMBHs) that have masses correlated with the velocity dispersion of their host galaxy stars in their central quasi-spherical "bulge", pointing to feedback and self-regulated growth of both the SMBHs likely formed from accretion onto, and mergers of, what were originally stellar mass BH "seeds" that might have been as massive as the ~100 $M_\odot$ BH remnants of the first stars. Thus the study of black holes on all scales impacts a wide range of key questions in astrophysics and motivated the original *EREXS* mission concepts[1,2] for a generalized BH survey mission. This *EREXS* mission concept focuses on the unique ability of a scanning high resolution (spectral and spatial) X-ray/hard X-ray mission to detect the highest redshift GRBs and flaring Blazars which can be identified and studied in outburst by prompt onboard nIR photometry and spectroscopy. This will enable the first systematic survey, with appreciable samples, of the first black holes, from stellar mass (GRBs) to the SMBHs (beamed AGN, flaring Blazars).

When catastrophic core collapse of a rapidly rotating massive star occurs at the end of its nuclear burning lifetime, under certain conditions (only partly understood – see Woosley and Bloom[3] for a review) a Gamma-Ray Burst (GRB) occurs which releases for the several solar masses (1 $M_\odot$ = 2 x 10^{33} grams) rapidly accreted into the BH a total isotropic equivalent energy of E_{iso}~$10^{52\text{-}53}$ ergs in hard X-rays and soft γ-rays with characteristic peak energies E_{peak} ~0.3 MeV that are detected as a GRB. Given the characteristic (long) GRB timescales of τ_b ~10 s for the radiation to emerge (in a jet), the GRB luminosity L_b ~E_{iso} /τ_b ~$10^{51\text{-}52}$ erg/s in detectable radiation is some ~10^4 times larger than the most luminous "steady" beacons from the distant-early Universe, quasars, which are persistently accreting SMBHs. It is this incredibly bright luminosity which makes the GRBs the most powerful probes to illuminate the structure of the early Universe. Conveniently, a GRB at redshift z has its time variability stretched by a factor (1 + z), so that the power law decay of the X-ray, optical and radio "afterglow" emission is dilated by this factor, thus enabling a GRB at z = 9 to be observed 10X earlier in the burst decay than a GRB at z =0.1 (say) observed at the same fixed delay.

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Within the past 3y, GRBs have superceded quasars as the most distant objects with measured spectroscopic redshifts (Fig. 1a). GRB080913 (z = 6.7)[4] and GRB090423 (z = 8.2)[5,6] both exceed the highest redshift quasar (z = 6.43) discovered[7] with the Sloan Digital Sky Survey. GRBs are thus the most distant as well as bright beacons with which to study the early Universe. This novel prospect, discussed in more detail in ξ2.1, is the primary science goal of *EREXS* and drives the overall mission design.

The study of SMBHs, both as accretion-powered active galactic nuclei (AGN), ranging from relatively nearby low luminosity Seyfert galaxies to distant extremely luminous quasars, and as non-accreting (dormant) SMBHs, drives the second primary science goal for *EREXS* and related objectives, as described in ξ2.2. Accreting SMBHs may be highly obscured by gas and dust in their host galaxies, or they may be dominated by powerful beamed jets. Both are poorly surveyed, and maximizing sensitivity to both requires wide-field hard X-ray imaging surveys. Dormant SMBHs can be detected by the tidal disruption flares (TDFs) they produce by occasionally shredding normal stars which pass too close.

The requirements to achieve the first two science goals enable the third: the study of transients of all classes, and the physics of the time-variable high energy sky. The wide-field imaging needed to discover GRBs and rare classes (e.g. luminous blazars) or phenomena (e.g. TDFs) associated with SMBHs, directly enable multiwavelength studies for the emerging and high priority (Astro2010) field of Time Domain Astrophysics, as described in ξ2.3.

We first summarize the three principal science objectives for *EREXS* in section ξ2 and describe how they relate to the 5 Science Objectives for a Next Astronomy mission given in NNH11ZDA018. A broad overview of the mission to achieve the science goals is given in section ξ3 with initial reference to the *EREXS* design (Fig. 6). We then follow with a detailed description of each of the two major telescopes and associated instruments proposed for the mission in ξ4, followed by the requirements for the spacecraft and mission plan in ξ5. In ξ6 we outline the proposed mission operations, and data analysis and the Guest Investigator (GI) program, followed by a brief Summary in ξ7.

2. PRIMARY SCIENCE OBJECTIVES FOR *EREXS*

2.1 Gamma-Ray Bursts as probes of the Early Universe

Again, GRBs (more specifically, "long GRBs", with durations ~2-1000s) have surpassed quasars and faint galaxies as the most distant objects for which redshifts have been measured by spectroscopy (cf. Fig. 1a). The highest redshift object so measured[5,6] is GRB090423 at z = 8.2 at which distance/time (by the standard concordant cosmology) the Universe was only ~630My old. Whereas recent *HST*/WFC3 observations[8] have given photometric redshifts (from Y and J band dropouts due to Lyman α absorption by neutral H in intervening galaxies) of objects which appear to be very faint (AB magnitude ~28.5) galaxies at z ~8-9, these are too faint for spectroscopy until observed with JWST after its launch in ≥2018.

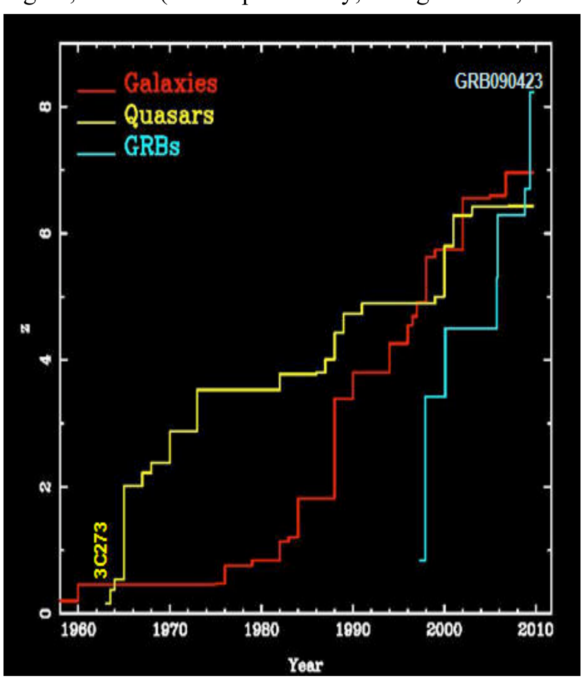


Figure 1. Maximum *spectroscopic* z of GRBs, QSOs and galaxies vs. time. Photo-z's ≥9 for both a GRB and HST/WFC3 galaxies have been reported.

The increase after 2004 in the maximum z for GRBs was due to the launch of the *Swift* mission[9] with its more sensitive and wide-field Burst Alert Telescope (BAT) and rapid slewing to point a narrow-field X-ray Telescope (XRT) employing direct focusing to provide ~3arcsec X-ray afterglow positions to enable imaging identifications with the UV-optical telescope (UVOT), and to allow deeper searches for optical or near infra-red (nIR) counterparts. Over the mission through July 2010, out of 526 GRBs detected and 441 XRT locations, 169 redshifts (all from ground-based telescopes) have been measured. The HXI and IRT of the *EREXS* design (Fig. 6 and ξ3) each have ~10X the sensitivity of *Swift*/BAT and Keck or VLT nIR spectroscopy (Table 1 and ξ4) so that virtually all GRBs will have redshifts measured on board. Given the fraction of GRBs detected above $z = 8$ as predicted[10] for *Swift* vs. *EXIST* (or *EREXS*, with comparable sensitivity) with the same GRB rate vs. star formation rate (SFR(z)). Normalizing to the actually measured 169 redshifts for *Swift* which are limited by ground-based telescope *coverage* and sensitivity, ~1.5 GRBs are expected above $z = 8$ from *Swift* which is consistent with that observed. For *EREXS*, with ~6X more GRBs expected above this redshift, but now with most having their redshifts measured with a very sensitive optical-nIR telescope (IRT) *on board* (see ξ3), ≥10 and likely ≥100 GRBs are expected to be measured at $z > 8$. This would enable the following use of GRBs as probes of the high-z Universe:

- *Measurement of EoR(z):* The large sample of GRBs at z ~8-12 expected from *EREXS* will provide in situ constraints on the epoch of reionization (EoR) and its evolution over redshift. This is the highest science priority for the mission and motivates the inclusion of the R = 1000 spectrograph for the IRT, which allows measurement of the shape of the red damping wing of the Lyman α absorption line to measure the ionization fraction in the local IGM vs. the host galaxy[12]. Simulated IRT spectra are shown in McQuinn et al[12] that demonstrate the feasibility, and Grindlay et al (2010) show that *Swift* GRB lightcurves redshifted to z = 12 indicate that a significant fraction (>50%) could be measured by *EREXS*. Since WMAP-7 CMB polarization data have obtained[13] an integrated constraint for the "midpoint" of the EoR to be at z = 10.5 ±1.2 for 50% ionization fraction, assuming a "flash" reionization model, the *EREXS* results *will cover enough sightlines to constrain the spatial patchiness of the "local" (at high z) IGM and the ionization fraction vs. redshift.*

- *Measurement of SFR(z):* Long GRBs trace the massive star formation rate, which in turn is a shorter timescale measure of the total star formation rate, SFR(z). The sample of at least ~2000 GRBs with redshifts and ≥300 with high resolution (R = 1000) spectra will provide the most comprehensive, and uniformly selected, *measure of how star formation and thus galaxy formation have evolved over early cosmic time.*

- *Measurement of Z(z):* Each GRB redshift spectrum will provide constraints on the metallicity, Z, of the host galaxy from absorption lines in its spectrum. GRBs bright enough (AB <20) to have high resolution (R =3000) spectra of their afterglows will provide direct measures of metal line strengths and thus well determined Z(z) values for perhaps ~500 GRBs vs. the limited sample now measured[11]. For the larger sample with AB >20-24, which will likely also include most with z >6, some can be measured at comparable resolution with JWST and future ~30m class telescopes on the ground (e.g. GMT/TMT/ELT).

- *Measurement of the Pop III era:* Finally, a deep high redshift sample of GRBs from *EREXS* could make the first detections of the gravitational collapse of Pop III stars, the primordial first generation of massive stars, which probably formed over a range of redshifts z ~15-30 and collapsed to form $\sim 10^{2-3}\ M_{\odot}$ BHs which may produce particularly luminous and long GRBs[14]. Their bright afterglow spectra arising from their shock-heated surrounding ISM would be devoid of metals and plausibly marked by HeII λ1640 absorption or emission from the pre-GRB surrounding HII region. Likewise, the afterglow X-ray spectra will be dust free and thus without absorption features[15] though these would be redshifted to the XUV. Since even JWST will not directly detect Pop III stars or the ISM spectra of their host primordial "galaxies" (dominated by dark matter halos), GRBs are the best hope to directly detect the (demise of) the first stars or, if Pop III stars make pair instability supernovae without GRBs (cf. Woosley and Bloom[3]), the first generation of Pop II stars from the initially enriched ISM. These are "guaranteed" to produce detectable/traceable GRBs.

As discussed in ξ3 and 4, the proposed *EREXS* payload (HXI and IRT) makes these ambitious studies possible out to even z = 19 given the 2.3μm cutoff of the IRT which in turn is set by the passive cooling (to a modest -30C) of the telescope optics to reduce thermal backgrounds at ~2μm by a factor $\sim 10^3$. ***EREXS* will provide unique constraints on Science Question 3, *How does large scale structure evolve*, particularly at z >6 and the Epoch of Reionization (EoR).**

2.2 Revealing obscured, dormant and the first (?) supermassive black holes to *EREXS*

Supermassive ($>10^6\ M_{\odot}$) black holes are fundamental building blocks of galactic nuclei and the surrounding central bulges of galaxies, as evidenced by the apparent correlation that the Bulge mass, measured by the Bulge stellar velocity dispersion, σ, is $\sim 10^3$ times larger than the SMBH mass measured by its accretion source properties and variability – the "M-σ relation". A recent best fit relation for a range of galaxy types with dynamical mass measures by Gultekin et al[16] gives scatter of ~0.2dex and a best fit relation $M_{SMBH} = 10^{8.12 +/-0.11}\ M_{\odot}\ (\sigma/200\mathrm{km/s})^{4.24}$. Yet, how do these masses evolve and over what ranges of z ? And since SMBH mass must increase over $<10^9$ y to power luminous quasars seen as early as z = 6.4, and this requires either or both rapid accretion and galaxy (and bulge) mergers, then most SMBHs at z >6 are heavily obscured while most at z ~0.1 are expected to be gas starved and dormant. Clearly this picture is too simple since, for example, 3 out of 4 of the closest AGN are obscured and the peak of the luminous quasar distribution with redshift is at z ~2. These are major questions that drive the science of a number of upcoming (JWST) and proposed (Athena or IXO-like) missions. But despite their power, their sample sizes are necessarily limited, as is their bandwidth. What is needed is a broad survey to measure SMBH demographics with minimal biases for obscuration or dormancy. As described in ξ3, this is where *EREXS* brings unique assets to bear on fundamental SMBH questions:

3. *Full sky coverage* for the survey, to enable discovery and measures of intrinsically rare objects (e.g. the highest luminosity objects, and jet-dominated systems, **particularly Blazars at high z**) or low duty cycle events such as tidal disruption flares (TDFs) expected[17] when main sequence stars encounter quiescent SMBHs.
4. *Multiwavelength imaging and spectroscopy*, from hard X-rays (up to 300 keV) to nIR with both extremes being optimum for minimizing absorption while at the same time maximizing the ability to distinguish star formation from accretion power. These are key requirements for attempts to chart SMBH growth over cosmic time.
5. *Repeated, or at least multiple, observations*, and simultaneously across multiple wavelengths, to measure spectral energy distributions (SEDs) without the confusion of non-simultaneous coverage *and* to measure spectral variability (particularly in the ~5-50 keV band) for the direct constraints on emission region size, and thus SMBH mass that these can provide. As discussed below (briefly), repeated measures of flux and time variability allow both SMBH (or BH) masses to be measured directly (given broad band spectral coverage) and for otherwise undetectable SMBHs in quiescence to be discovered by their occasional TDFs.

The scanning all sky survey proposed for the first 2y of the *EREXS* mission and which then triggers a 3y followup pointing program (see ξ3), together with the sensitivities and configuration of the instruments, have been designed to measure SMBH demographics which will constrain their origin and evolution.

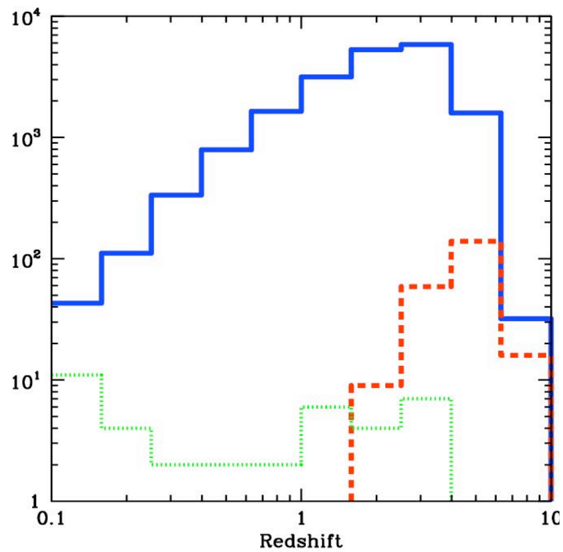


Figure 2. Expected redshift distributions of Blazars (see text; from Della Ceca et al[18].

*Blazar probes of **first SMBHs**:* The redshift distribution expected for blazars (AGN with non-thermal beamed emission in jets) is shown in Fig. 2b and is the most dramatic promise of the SMBH survey expected for *EREXS*. This plot, also from DC09, is taken from Fig. 15 of Ghisellini et al.[20] (G10) and based on the luminosity function for blazars derived by Ajello et al.[21] from the 38 blazars (green dotted curve) detected at 15-55 keV in the BAT all-sky survey. The red dashed curve is for blazars with $L_x > 2 \times 10^{47}$ erg s^{-1} for their rest frame 15-55 keV luminosities, the luminosity limit of the 10 most luminous BAT blazars all at z >2 which were considered in detail by G10. All of these are Flat Spectrum Radio Quasars (FSRQs) with their inverse Compton peaks in the hard X-ray/soft γ-ray band (and so generally not detectable by *Fermi*/LAT), and for sub-Eddington accretion, their extreme luminosities imply that all must have SMBH masses $>10^9$ $M_\odot$. Thus, the very large Blazar sample expected will likely include extreme objects at z >6 that are *sensitive probes of the epoch of growth of SMBHs*. As shown by G10, the BAT blazar 2149-306 at z = 2.35 could be detected in the 2y *EREXS* scanning survey if it were at z =8, at which the short growth time might require major mergers and/or super-Eddington accretion. These objects might never be found in narrow-field surveys but could be then identified in the pointing phase of the *EREXS* survey by their continuum power law spectra from which the IRT would measure the redshift directly by the Lyman break in their redshifted spectra.

Obscured SMBHs: The yields of unobscured (Compton thin) vs. obscured (Compton thick) AGN expected from the scanning 2y survey with flux limit F_x(10-40 keV) ≥8 x 10^{-13} erg cm^{-2} s^{-1} would yield ~28000 Compton thin, ~1400 Compton thick, and – most notably – some 19000 blazars, or ~2 orders of magnitude larger than the current totals at hard X-ray energies (>10 keV) derived from any hard X-ray mission, most notably *Swift*/BAT or *INTEGRAL*/IBIS. The small field of view of future focusing hard X-ray missions (e.g. *NuSTAR*) will give smaller samples of Compton thick AGN despite their significantly greater sensitivity. The distribution of Compton thick objects, with absorption column densities NH ≥10^{24} cm^{-2}, is particularly uncertain, being based primarily on the relatively small sample size from the XMM HBSS used (DC09) to scale to *EREXS* sensitivities and energy bands. Although Compton thick objects are by definition detected in their continuum spectra only above their ≥5 keV low energy cutoff energies (often accompanied by strong 6.4 keV fluorescent Fe line emission from surrounding gas), their "unabsorbed" high energy spectra are still reduced by Compton scattering. Thus for any flux limited survey, their apparently lower luminosity actually detected gives them a lower redshift distribution than the Compton thin sample. The most recent constraints on obscured (Type 2) AGN, with NH ~ 10^{22} cm^{-2}, but not Compton thick, is from the *XMM*-Cosmos wide field survey[19]. The fraction of these objects is much higher, reaching 90% at low luminosities (L_x ~10^{42} erg s^{-1}), but falling to ~20% at luminosities 3 orders of magnitude larger. A large sample of objects like the luminous Type 2 QSO "XID 2028" discovered by Brusa et al.[19] would be found in the *EREXS* survey.

SMBH mass measures: Dynamical mass measures (not limits) for SMBHs in galactic nuclei are only available for 51 systems (Guletkin et al[16]), yet anchor the M-σ relation which in turn drives the discussion of black hole feedback in galaxies vs. SMBH growth. As noted in Guletkin et al, the dispersion in the relation is particularly large in spiral galaxies, and various sources of systematic error remain problematic. It is thus important to use independent techniques to measure or constrain SMBH masses, particularly for the luminous accreting systems (either obscured or not). X-ray timing offers just such a method, since accreting BHs show strong correlations between their variability timescales and BH mass when scaled for accretion rate as given by the bolometric luminosity. McHardy et al.[22] showed that a sample of 10 X-ray bright Seyfert galaxies with variability timescales T_B measured by the breaks in their power spectral density (PSD) as well as bright galactic BH X-ray binaries (Cyg X-1 and GRS1915+105) all fell on a relation $T_B \propto M_{BH}^{2.1}/L_{bol}^{0.98}$ for AGN (and BH-XRBs) with BH mass M_{BH} and accretion luminosity L_{bol}. The 2y scanning survey will cover the full sky and measure the variability of all objects on timescales τ over which significant (>5σ) detections are made, which for the background limited wide-field HXI are $\tau \propto 1/S^{0.5}$, where S is the source flux in some band. Since the *EREXS* AGN logN-logS counts has slope -3/2, the number of AGN measureable should scale as $N(>T_B) \propto T_B^{3/4}$ as is approximately evident in Fig. 3 for AGN of the types as noted. To measure the PSD and a break timescale T_B requires that lightcurves contain at least ~300 points (ideally >10^3) and thus range of timescales. From Fig. 3, T_B measures or limits, and values for M_{SMBH}, could be derived from a sample of ~400 AGN (a ~20X larger sample than now available from RXTE). **Thus *EREXS* will provide unique constraints on Science Question 2, *When and how did supermassive black holes grow?***

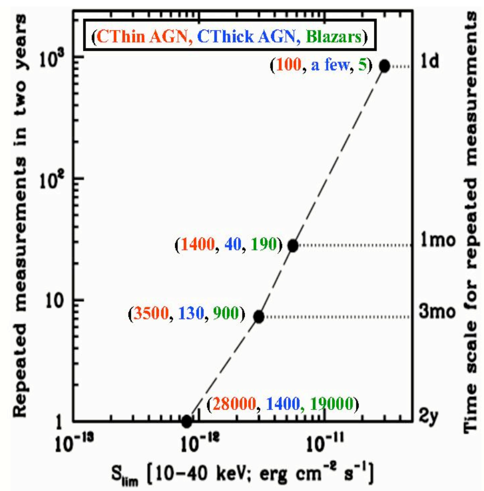


Figure 3. AGN numbers vs. minimum timescale observed in 2y survey (from DC09).

2.3 Time Domain Surveys

Finally, in the era of *LSST, ALMA* and *LOFAR*, *EREXS* will open new windows for Time Domain Astronomy (TDA) surveys and detailed temporal studies. The same repeated observations with the 2y scanning and then 3y pointing programs enable a wide variety of transients and variables to be discovered and studied as shown in Fig. 4. Each of these classes of objects can be explored in detail, without interference to the others, during the course of the scanning survey. We mention two with direct connections to the GRB and SMBH science priorities (ξ2.1, 2.2):

Short GRBs vs. Advanced LIGO: Short GRBs (SGRBs), with observed durations (T90) <2sec and in fact usually <0.5sec, are less luminous than the long GRBs discussed in ξ2.1. The leading model for their production is the merger of two neutron stars, or possibly (in some cases) a NS-BH merger. The NS-NS merger model can be directly tested by the coincident detection of the SGRB with the gravitational wave (GW) signal (chirp)

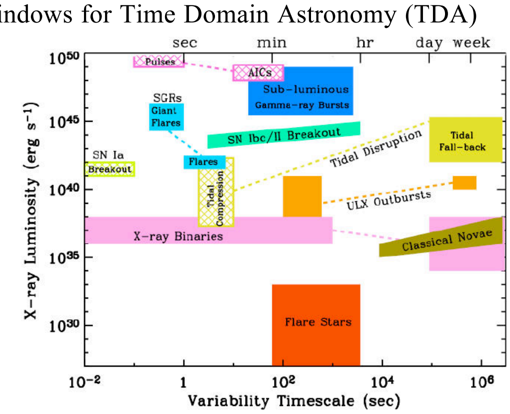
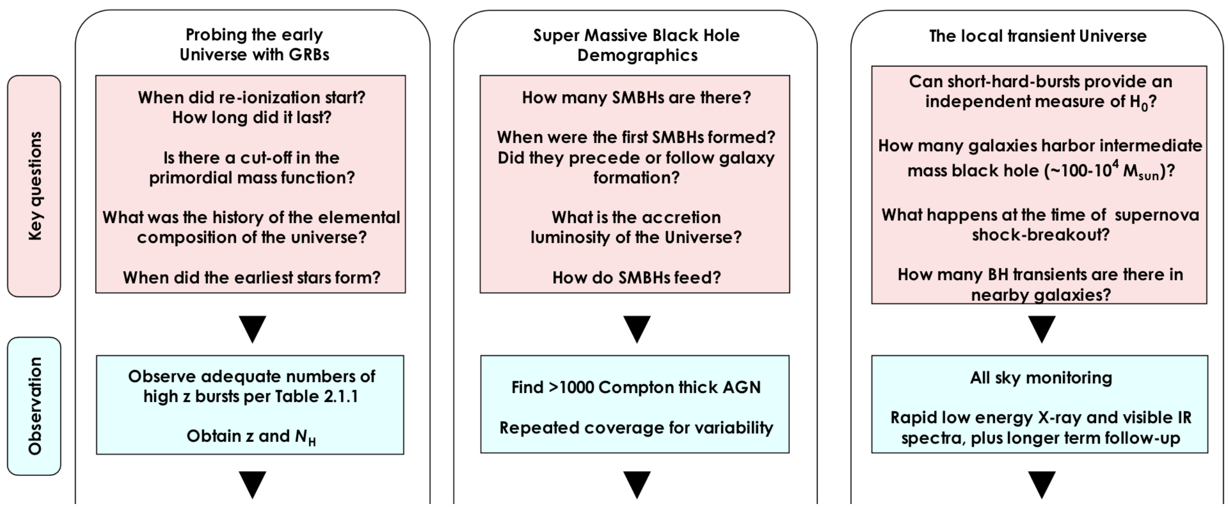


Figure 4. Lx vs. timescale for *EREXS* transients.

produced during the final inspiral and that for some can be detected with Advanced LIGO (>2014) out to large enough distances (~400 Mpc) that current estimates for total SGRB rates will produce several events per year. Depending on the (still) uncertain beaming of SGRBs, a fraction of these would be detected and precisely located by *EREXS* as SGRBs, thereby allowing a precision (<2%) measure of the Hubble constant *for each such GRB*[25]. The GW vs. EM signal of a NS merger will constrain the NS-EOS. **Thus *EREXS* will constrain Science Question 5, *How does matter behave at very high density?***

Tidal disruption flares: The detections of TDFs due to the disruption of a (usually) main sequence star by a non-accreting (and so dormant) SMBH continue to mount along with models (Gezari et al[31]). The soft-X-ray luminous flares that marked their original discovery with *ROSAT* would be (generally) detectable above the 5 keV threshold for HXI. However, a TDF but becomes much more detectable if the shock induced by the disruption event produces a jet and thus a prompt hard X-ray power law spectrum as was discovered by *Swift*/BAT for J1644 (Burrows et al[46]). With 10X BAT sensitivity and thus 10^3X survey volume, *EREXS* should detect ~10-30 y^{-1} out to comparable z ~0.7. These are detected as candidate TDFs by finding new scanning survey sources in the most recent ~3-10d (sliding detect window) of integrated sensitivity with HXI positions (all are <20") coincident with galaxy nuclei. As candidates are found, a short (1-2ksec) pointing is triggered to verify the source in the more sensitive NF-HXI telescope and IRT to obtain a high resolution (0.15" pixels) IRT image in its 4-bands (ξ4.3). Confirmed detections then trigger spaced (~1mo.) followup imaging and spectra to follow the TDF decay and constrain the still uncertain energy release timescales. The large TDF sample built up over the 5y mission would allow detailed SXI and IRT studies of their galactic nuclei to constrain their



Requirements:

GRBs: >3X BAT sensitivity (15-150 keV) ***and >10X sensitivity <15keV and >200 keV; IRT for IDs, z's and spectra <10arcsec HXI 90% conf. locations for >10σ sources for prompt IDs, redshifts & R = 1000 spectra with IRT***

SMBHs: >10X BAT sensitivity (<20 keV) for high-z Blazars and AGN followup spectra

Figure 5. Flowdown from science objectives to mission requirements for *EREXS*.

otherwise quiescent SMBH masses from their measured bulge velocity dispersions and the M - σ relation. This then provides the "independent test" needed for the M - σ relation itself and allows ***EREXS* to constrain Science Question 4, *What is the connection between SMBH formation and cosmic feedback?***

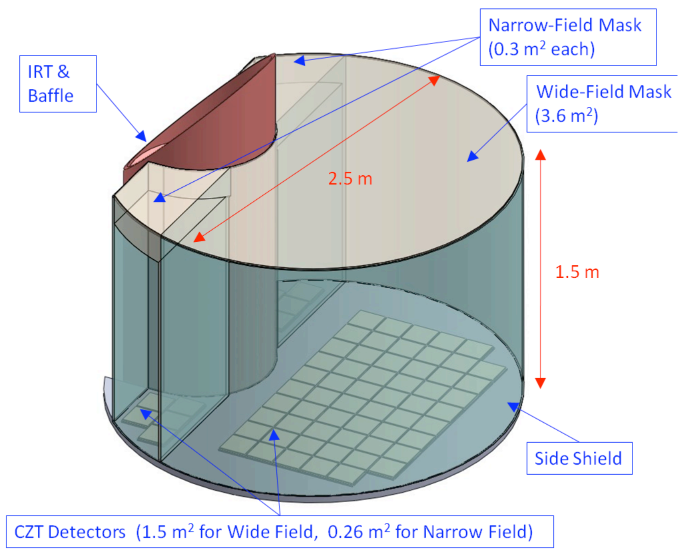
Given the primary science objectives, the "flowdown" requirements for the *EREXS* mission are summarized in Figure 5.

3. OVERVIEW OF THE *EREXS* MISSION

The *EREXS* mission is a much less massive, but comparably sensitive, and with new followup p;ointing capability, than the *EXIST* mission proposed to the 2010 Astronomy and Astrophysics Decadal Survey (Astro2010). *EREXS* is a Medium class mission designed for launch on a launcher such as the Delta II (or equivalent for future capability) with ~2000kg LEO lift and ~2.5m payload fairing. or (the minimal lift/cost launcher with 4m diameter fairing). The nominal lift capability of the Delta II 7920 and total mass (with contingency) for the mission would allow a KSC launch into a moderately low inclination of i = 15^o. We first summarize the payload and then the mission plan.

3.1 Mission payload

The overall payload is shown in Fig. 6a, with the HXI and IRT telescopes co-aligned mounted on the spacecraft, and in Fig. 6b from the top-down view. The top-level characteristics of the telescopes and mission are given in Table 1.



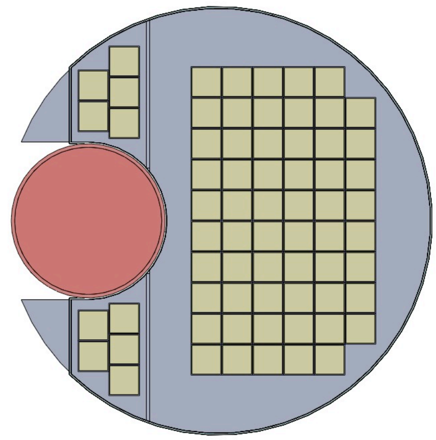


Figure 6. Left, a) *EREXS* mission telescopes HXI and IRT (ξ4.1 and 4.2) mounted on the spacecraft (S/C). HXI has wide-field (scanning) and narrow-field (pointing) components with identical CZT detectors but differing masks; Right, b) Top-down view of payload.

Table 1: *EREXS* mission parameters.

Parameters	**Values**
Orbit	600 km, 15º inclination, 5yr mission
Mode	Zenith orbital scan (2yr); inertial pointing (3yr)
High Energy Telescope (**HXI**): Coded aperture, WF & NF imaging 1.8m^2 CZT: 58 WF modules (scanning) 10 NF modules (pointing)	5–300 keV, 80º×50º FoV (WF), 7^o x 7^o (NF), ≤20″ positions (90% CL) 0.08–0.4 mCrab in1yr survey; ~1mCrab in1d (5-100 keV, 5σ) 10mCrab in 100s pointing; 1mCrab in 10^4 s ptg. (5-100 keV, 5σ)
Optical/IR telescope (**IRT**): 0.8m aperture R-C	0.3–2.2 μm, 4′×4′ FoV, 0.15″ resolution AB~23 mag in 100 s; AB ~21, 19 for R = 30, 1000 spectra in 1000 s
Spacecraft (S/C)	Pointing: 2″ stability; Aspect: 2″ (90% conf.)
Mass	2150 kg (incl. 30% contingency and 156 kg propellant)
Power	1180 W (incl. all instruments and S/C with 30% contingency)
Telemetry	30 GB/day; realtime (TDRSS) GRB downlinks
Launcher	Delta II 7920 with 2.9m fairing
Cost range (GSFC Price H vs. Astro2010, scaled for mass & power from *EXIST*)	$400M (GSFC Price H) vs. $900M (Astro2010 for 2.5X larger HXI, 1.1m IRT, larger S/C, AtlasV launch and 5y mission ops.)

3.2 Mission operation

The overall mission design is centered on the wide-field HXI to detect, measure and accurately locate GRBs, SMBHs and transients in its medium-hard X-ray (5-300 keV) band. For GRBs and bright (>10mCrab) transients, the positions are computed on board (<10sec, or event duration) and if warranted (e.g., for all GRBs), a prompt S/C slew is executed if allowed by Sun avoidance (>40^o offset required), Moon or Earth limb constraints. Slews are possible within ~150sec to achieve stable pointing (<2”) of the HXI, SXI and IRT on the <20” position computed by the HXI. For GRBs or unknown transients, the followup NF-HXI imaging will yield a <20arcsec position typically within 100sec, which is compared with the 100s image simultaneously acquired in 4 bands by the IRT for an obviously variable counterpart. If found, the IRT tip-tilt mirror (see ξ4.3) puts the object onto the long-slit for a spectrum (in all 4 bands) at R = 1000 if the magnitude from the 100s image are AB <20 or onto the R = 30 long slit if AB <23 or the R =30 objective prism if the ID is uncertain. If none of these conditions are met, a deeper (300s) image is obtained and the process repeated. At each stage (i.e. after first 100s pointing), HXI and IRT images (object positions and magnitudes) are sent down via the rapid TDRS link, which has already sent down the HXI position for the GRB (or transient) that initiated the slew.

During the first 2y of the nominal 5y mission, *EREXS* is in a scanning mode, with its view axis pointed at the local zenith but ~25^{o} North and then ~25^{o} South of the orbital plane on alternate orbits. This allows the 110^{o} x 70^{o} FoV (FWZI) of the HXI to scan the whole sky every two orbits (3h) and achieves the following advantages over a survey done with a fixed-pointing large FoV coded aperture telescope (e.g. *Swift*/BAT or *INTEGRAL*/IBIS): i) larger sky coverage per unit time, which is particularly important for long GRBs at high redshift which may have T90 durations (1 + z) times longer than their counterparts at low z; ii) longer exposure times for any given source since it is observed for ~20min (=FoV diameter/4^{o}/min scan rate) every 3h, and iii) ~1.5X increased sensitivity for *scanning* coded aperture imaging[45] since systematics in the pixel-detector plane are averaged more completely than "dithering" pointing as done by *INTEGRAL*.

Since typically ~1-2 GRBs per day are expected, and each is followed by ~1-3 orbits of pointing (depending on brightness) with the SXI and IRT, the scanning survey is in fact ~75% of the first 2y, with the remainder in pointing mode. During these GRB pointings, the HXI can and will trigger on new GRBs, though slews to these may be inhibited for GRBs determined to be high redshift (usually within the first ~300s after trigger) so that their high resolution nIR spectra can be obtained without interruption. Due to its small (4arcmin; Table 1) FoV and readout electronics based on *JWST*/NIRSPEC (see ξ4.3), the IRT only operates in pointed mode and so is taking data for ~25% of the scanning mission phase and 100% of the following 3y pointed mission phase, and thus for ~3.5y of the 5y mission.

For the 3y pointed phase of the mission, survey sources are observed in the HXI and IRT. The "new" narrow-field portion of the HXI (NF-HXI) with low CXB background provides ~10X the sensitivity of BAT at 15-30 keV and ~100X increase at 5 – 15 keV. The primary targets are i) the candidate Blazars, particularly those with high z, ii) the candidate obscured and Compton thick (CT) AGN and iii) the candidate TDFs and other extreme variables found in the HXI-SXI scanning survey. The blazars are found by selecting on source colors for sources with hard spectral and υF_{υ} fluxes in HXI (e.g. 5 -10 vs. 10 –20 keV) that exceed those in eROSITA (e.g. 1.5 – 3 vs. 3 – 6keV), which would point to SEDs similar to those for the BAT blazars as shown by G10. Obscured and candidate CT AGN are similarly identified as sources with low energy absorption. Any sources detected only by HXI (at 5-10 keV and 10-20 keV) and not by eROSITA are candidates to be either Blazars or CT AGN and so are also prime targets for the pointed followup survey. The total expected AGN candidates (i and ii) are ~19,000 and 1400, respectively (Fig. 3). For identification and classification by the HXI and IRT of the sources, the pointing survey will typically require 1-2 orbit pointings (2ksec each). Thus with 16 orbits/day ~20000 objects can be measured and accomplish science goals in a 3y pointing program.

4. THE *EREXS* TELESCOPES

The two telescopes and instruments proposed for the *EREXS* mission are shown in Fig. 6 and summarized in Table 1.

4.1 Hard X-ray Imager (HXI)

The earlier *EXIST* design for the imaging CZT and the large area coded aperture telescope, the HXI (see Fig. 6 and Table 1), has been described by Hong et al[34,35,36]. Here we describe changes made for *EREXS*.

First, we have now increased the HXI sensitivity for the followup pointed observations on survey sources discovered in the 2y scaning survey.

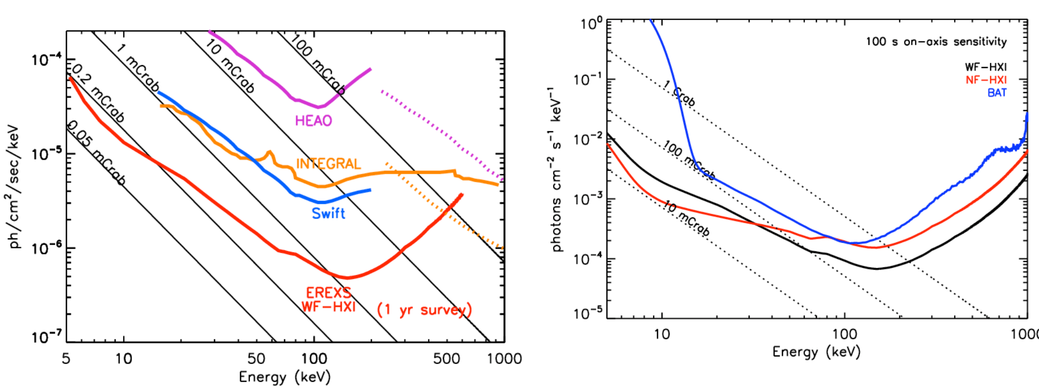


Figure 7. Left, 1 year survey (full sky) sensitivity (5σ, 5-100 keV) with WF-HXI; Right, 100s pointing sensitivity with NF-WF-HXI.

This is done with the Narrrow-Field HXI (NF-HXI) coded masks (location shown in Fig. 6) which are two identical coded masks (0.3mm Tungsten each, with 1.2mm pixel pitch) and spaced by 2cm. These act as 7^{o} X 7^{o} (FWHM) collimator to reduce the dominant CXB background by a factor of ~100 below that in the larger area and FoV (80^{o} X 50^{o}, FWHM) WF-HXI imager. This allows a factor of ~10 improvement in pointing sensitivity per unit time than that achieved by *Swift*/BAT so that early afterglows (e.g. afterglow flares) can be directly detected with HXI in the immediate pointing phase to further refine the WF-HXI positions (<20arcsec) measured during the scanning. Even more important, for followup pointings on survey sources in the pointed mission phase, the significantly increased sensitivity allows followup spectra and timing studies to be conducted. The HXI fine position and spectral resolution allow <10-20 arcsec positions from the HXI to enable prompt IRT identifications. The HXI detectors and full design of each module (Fig. 6) have now been developed and tested, with excellent spatial and spectral resolution. A first balloon flight test of a flight module will be carried out in September, 2012. Finally, the multi-pixel readout (hit pixel plus near-neighbors plus reference pixel), combined with ~0.7mm depth sensing for each event at >200 keV (Allen et al[37]), means that Compton imaging and polarization measurement is possible, particularly for GRBs.

The successful balloon flight of *ProtoEXIST1*, the first-generation prototype for the imaging CZT, with 2.5mm pixels, read out by an ASIC below and close-tiled to form a reduced size DM, is discussed by Hong et al[36] and the detector and telescope integration by Allen et al[38]. The currently successful development of the close-tiled CZT imager with 0.6mm pixel size for *ProtoEXIST2* and then the final prototype, *ProtoEXIST3*, are also described in Hong et al[36] 2010a, with a balloon flight test of *P2* (together with *P1*) planned for September 2012.

4.2 Optical – near Infra Red Telescope (IRT)

The IRT is the truly novel telescope on *EREXS*. It combines unprecedented near-IR sensitivity, obtained by passively cooling (on dark sky) the primary mirror and subsequent mirrors to -30C, which reduces thermal backgrounds at 2μm by a factor of $\sim 10^3$, thereby achieving zodiacal light background levels that give sensitivities and speeds at 2μm that are 10X that of the 10m Keck telescope. The IRT design by Kutyrev et al[44] has an innovative combined imaging and spectroscopy (low and high resolution) focal plane for simultaneous imaging or spectroscopy in 4 bands from 0.3 – 2.2μm with no moving parts or filter choices to be made. The telescope itself is a 0.8m telescope similar to that designed by ITT for the *GeoEye* mission now in orbit (Fig. 8a) but modified (for IRT) as a simpler Ritchey-Chretien. The focal plane design and overall imaging vs. spectroscopy optics and optical bench (Fig. 8b) were designed at GSFC by Kutyrev et al[44]. The focal plane enclosure is actively cooled ~15K below the passively cooled ambient mirror temperature (240K). The two IR detectors are H2RG Hg-Cd-Te detectors (2K x 2K) as developed for NIRSPEC and NIRCAM on *JWST* and the two visible HyVISI detectors employ active pixel Si detectors and the same Teledyne SideCar ASIC readout as the H2RG detectors. Thus all focal plane elements have high TRL. The tip-tilt mirror and 10Hz servo system provides autoguiding (0.15" stability) over a 6" range so that the <2" inertial pointing stability of the S/C is readily accommodated for precision pointing. The tip-tilt is also used for small offsets – e.g. from a ~10arcsec HXI source position to center up an object on a 0.3" slit. Given this optical design and the IRT parameters summarized in Table 1, the nominal sequence of IRT observations for a GRB, following a rapid slew to a <20" source position computed by the HXI, would then be as shown in Table 2.

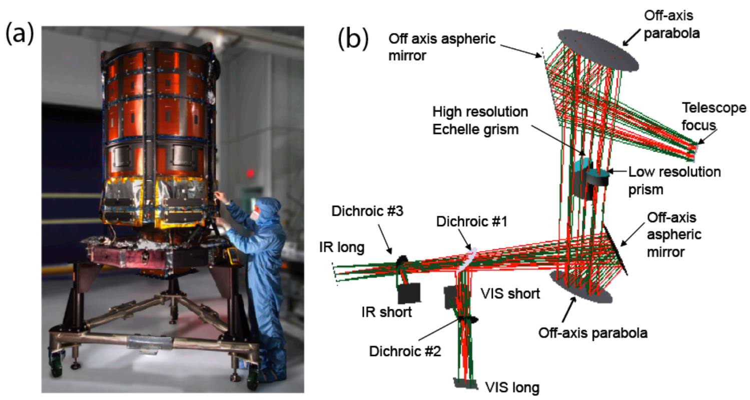


Figure 8. Left, a) 1.1m ITT optical Earth-imaging *GeoEye* telescope and prototype for the smaller 0.8m IRT; Right, b) optical-nIR focal plane design for the IRT (from Kutyrev et al[44]).

The IRT observation sequence for a GRB identification and followup spectroscopy shown in Table 2 is for a "clean" high latitude GRB field, which will be typical for most. The observation sequence shown extends only through the first orbit. Most GRBs will be followed for at least 2 orbits; all at z >4 -5 will be followed for ≥3 orbits. In the second orbit, and subsequent orbits (if obtained later), a deeper set of images (4 bands) would also be obtained for host galaxy identification and morphology or limits (e.g. 4 orbit exposures should reach AB ~27) to guide followup *JWST* observations (for z >7-8 GRBs).

For SMBH/AGN and transient source IRT observations, the "typical" observation sequence is similar to that above,

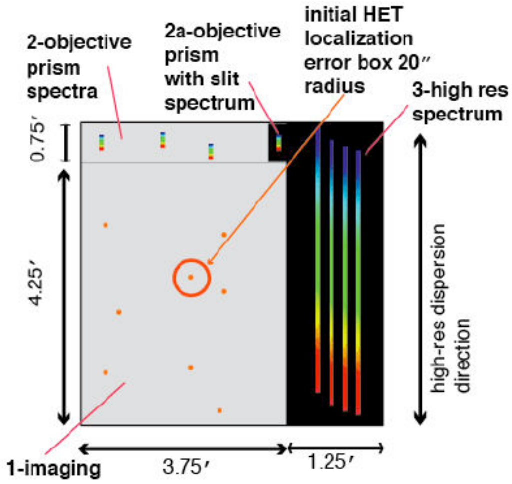


Figure 9. Allocation of 2K x 2K detector area (optical and IR) for imaging vs. spectroscopy (from Kutyrev et al[44]).

Seq. #	Time (s)	Observation
1	100	Initial 4-band image (AB~23)
2	300	Initial R=1000 spectrum if Seq. 1 AB<18 obj. @<10" from HXI pos.
or 2a	300	Initial R=30 slit spectrum if Seq. 1 AB<21 obj. @<15" from HXI pos.
or 2b	300	Initial R=30 objprism spec if Seq. 1 AB<22 obj. @<30" from HXI pos.

Table 2. Autonomous IRT measurement of GRBs

though here the final identification may require several trial spectra (e.g. for high-z Blazars, which will in many cases be continuum spectra objects and so not readily distinguished from metal poor stars). However for most newly discovered AGN in the scanning survey (Fig. 3), the typical range of X-ray/optical flux values would predict optical/nIR magnitudes AB ~19-20 so that their initial identification as emission line objects by using the R = 30 objective prism or slit will provide rapid (<300s) identifications to then enable R =1000 spectra for detailed studies (e.g. reverberation line mapping).

5. SPACECRAFT AND MISSION PARAMETERS

As part of the ASMC (Astrophysics Strategic Mission Concept) Study carried out for *EXIST* in 2008, during which the detailed design of the three primary telescopes and their instruments was developed with an engineering study at the NASA/GSFC Instrument Design Lab (IDL). The spacecraft (S/C) and systems resources required to support (power, point, deliver data, etc.) the telescopes were also studied in the Mission Design Lab (MDL). The principal components of the S/C design are incorporated into the smaller S/C and requirements for *EREXS*, with only two smaller telescopes.

6. MISSION OPERATIONS, DATA PROCESSING AND GUEST INVESTIGATION

The data command and data flow routing to the *EREXS* mission and both the Mission Operations Center (MOC), at GSFC, and the Science Operations Center (SOC), at the Harvard-Smithsonian Center for Astrophysics, are understood. Given the high data rate from the HXI and the scanning requirement for high time resolution, photon event data are brought down rather than binned detector data. Real-time data for GRBs are brought down for rapid GCN distribution (within ~10sec of a burst) and full survey data are rapidly made available for a Guest Investigator program.

7. SUMMARY

The *EREXS* mission offers a uniquely powerful, multi-wavelength and multi-scale (both spatial and temporal), new resource for unlocking some of the most fundamental astrophysical problems and priorities for *PCOS* science. Its in situ measurements of the Early Universe by prompt detection, imaging and spectra of GRBs – from hard to soft X-rays to the near Infra-red – will enable the most direct probes and measurements of the first (or nearly first) stars and galaxies. That objective alone should justify such a mission, but it also provides the tool needed to study the most extreme black holes – from the first supermassive which might be revealed as luminous Blazars, to those that are obscured at lower X-ray energies, to those that are dormant and may lurk in (bulgeless) galaxies that by our current paradigm should not contain them. *EREXS* would open the high energy TDA Universe as never before to answer fundamental questions probed by black holes. It will measure the highest-z SMBHs (Blazars) and detect and measure IR spectra of the highest-z GRBs to probe the late, middle, and possibly earliest phases of the EoR.

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