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GRBs as probes: increasing both the high-z and short GRB sample

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Abstract. The promise of GRBs as probes of the high-z Universe is clear, given the detection of GRBs at z = 8.3 and ~9.3 within 6d in April, 2009. These were both hampered by their (late) near-IR followup, suggesting that the large high-z GRB sample is limited currently by lack of prompt JHK photometry and spectroscopy within the first few hours from trigger. With no planned space-borne near IR telescope, for prompt GRB photo-z's or high resolution spectroscopy, the power of GRBs to probe the Early Universe will depend on a possible 3.5m Chinese telescope in the near-space like environment of Dome A in Antarctica or a modest network of 4m class telescopes (proposed here) for rapid response imaging and spectra, as needed also in the era of LSST. With the coming advent of Advanced LIGO, short GRBs will be vital as probes of the gravitational wave Universe. Just as with long GRBs as probes of the high-z Universe, it is essential that we are ready with a sensitive GRB imaging mission. For sGRBs, with their lower luminosity and conspicuously faint afterglows as well as likely wider-angle beaming factors, it is advantageous to be able to locate them precisely from their prompt emission (i.e. without afterglow detectons) to identify their host galaxies within the projected ~300-600 Mpc survey limits for ALIGO. This will not only open the GW-EM window, but also allow precision measures of the Hubble constant.

Key words. Stars: Gamma Ray Bursts – Stars: cosmological probes – Stars: Population III – Short Gamma-Ray Bursts – Gravitational Waves

1. Introduction

GRBs are the most promising *objects* for direct probes of the high redshift Universe. With prompt luminosities at least 4 orders of magnitude larger than the most luminous active galactic nuclei (AGN), including relativisticaly beamed blazars, GRBs are the true beacons to directly trace the star formation rate (SFR) in the early Universe provided that redshifts can be obtained for significant samples with known selection effects. But GRBs can do more. Their enormous flux from the time-dilated late stages of prompt emission as well as the (occasional) relatively bright flares in early stages of the afterglow provide a unique, but fleeting, opportunity to obtain rest frame high-resolution optical and near infrared (nIR) spectroscopy to measure absorption line equivalent widths and thus metalicities in the host galaxy as well as intervening galactic haloes. When applied to GRBs with redshifts similar to and beyond those currently still largest, GRB090423 and

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GRB090426B (Tanvir, these proceedings), the power of GRBs as probes is obvious: even JWST with its unparalled depth and both nIR and mid-IR sensitivity cannot do the required high resolution (R $\gtrsim$ 3000) spectroscopy on the intrinsically faint (typically $\lesssim 10^{9.5}\ M_{\odot}$) host galaxies at z $\gtrsim$ 9 since likely minimum JWST slew times to such a GRB are at least 1-2 days. Spectroscopy with resolution R $\gtrsim$ 3000 of the damped Lyα red wing is needed for measures of the host galaxy vs. local IGM neutral H fraction, to trace the growth of the epoch of reionization (EOR) with z, as previously proposed by Grindlay et al (2010) for the *EXIST* mission.

Whereas the promise of (long) GRBs as probes of the early Universe is here today, since the existence of GRBs at cosmologically interesting redshifts (z $\gtrsim$ 8-9) during the EOR has been demonstrated, the promise of short GRBs (sGRBs) as probes of absolute distance measures by their simultaneous detection with gravitational wave (GW) obseratories must await the implementation of ALIGO and advanced VIRGO in ~2016 (see Cardonati, these proceedings). As described in Bloom et al 2009, the absolute distance of a sGRB derived from its GW chirp signal of the associated NS-NS (or NS-BH) merger (the currently favored sGRB model), when compared with the redshift distance obtained from an optical ID enabled by a "precise" position from the GRB prompt or afterglow electromagnetic emission and the corresponding redshift, will enable a ~1% measure of the Hubble constant. The combined ALIGO and AVIRGO network will likely have sGRB detection limits of ~300 and 700Mpc for NS-NS and NS-BH mergers, respectively, so the H_o measures will be local. However for sGRBs detected in gamma-rays, the distance limit may be somewhat more, out to perhaps ~1Gpc, since for more nearly face-on mergers (when the sGRB jet is approximately aligned towards us), the GW signal is enhanced (relative to the orbital plane. If future more sensitive GW detectors are developed following ALIGO (and AVIRGO) that could detect sGRBs out to their current *Swift* median redshifts of z ~1 for sGRBs, then measures of the evolution of H(z) could be derived from sGRBs.

To make use of GRBs as probes of either the early Universe with long GRBs or the tantalizing measures of H(z) with sGRBs and GW detections, significant samples are needed. Unfortunately, despite the great discoveries in both domains made with *Swift*, the sample sizes are still small: just 2 GRBs at z $\gtrsim$ 8 and only 13 sGRBs (with T90 $\lesssim$ 2sec) with redshift measures out of a total of only 51 detected, or ~10% of the total *Swift* GRB sample. Redshifts from at least 20 high-z GRBs are needed to map the SFR(z) relation and to enable prompt R $\gtrsim$ 3000 spectroscopy for studies of Z(z) and the EOR. A similar (10X) increase in sGRBs is needed in the ALIGO timeframe. In this paper we outline possible new ways to increase the redshift yield of long GRBs from ground-based IR telescopes and a new hard X-ray survey and GRB mission with good sensitivity and localizations for prompt sGRBs that could be operating in the early years of ALIGO.

2. Prompt redshifts for GRBs at z $\gtrsim$ 7

The major challenge to expand the high-z GRB sample is to obtain prompt redshifts. The *EXIST* mission proposal (Grindlay et al 2010) did this with a 1.1m IR telescope (IRT) with both imaging and R = 30 and 3000 prompt spectroscopy on board in response to wide-band GRB triggers with ~5-10X the sensitivity of *Swift*. Unfortunately, the Decadal Survey costed this proposal a factor of ~2.4X higher than GSFC costing and it was not considered. Even more unfortunate, no medium or large NASA missions, apart from JWST, will fly in this decade. The two recent Explorer proposals, *Lobster* and *JANUS*, proposed ~50cm class IRTs for prompt on-board nIR redshifts that would alert large ground based facilities for higher resolution nIR spectra. The fact that neither was accepted for Phase A study is a tragedy for GRBs as probes and Time Domain Astronomy (TDA), generally! Since there now is no IRT planned for space with both sensitivity and resolution as well as rapid slew capability, the high-z Universe can, for most of the coming decade, only be probed with GRBs using ground-based IRTs.

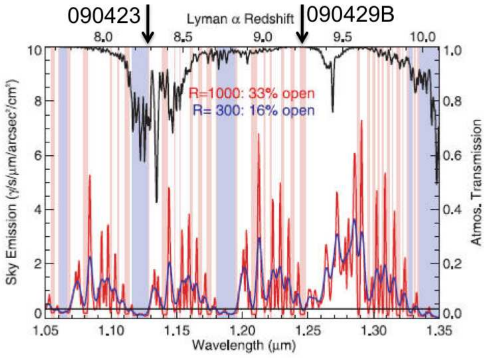

Fig. 1. OH emission and atmospheric transmission in J-band-IR (adapted from Barton et al 2004). Both high-z GRBs fall in "windows".

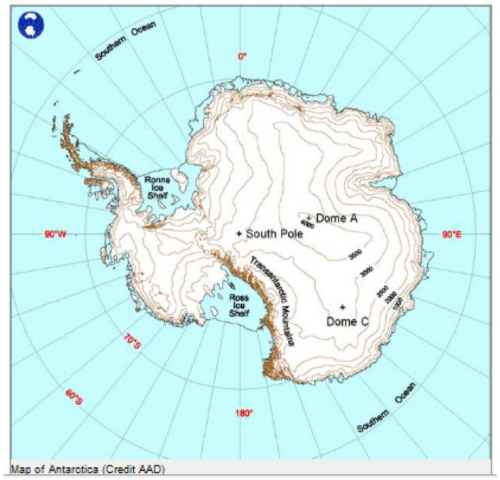

Fig. 2. Dome A location and elevation on Antarctica.

Given the large background of atmospheric OH emission lines at $\lambda \sim 0.8$ - 2.2μm, photo-z sensitivities are degraded and followup spectroscopy (e.g. for the redshift evolution of metalicities, Z(z)) should be done at resolutions R $\gtrsim$ 3000 to look 'between the lines'. Figure 1 shows that the two high-z GRBs identified thus far had their Lyman breaks in relatively low obscuration "windows". Thus, although "dark GRBs", with no optical or JHK detections of afterglows, may indeed be dominated by highly obscured GRBs (Greiner, these proceedings), the "OH Forest" must also contribute to loss of sensitivity to the Ly-break and high-z GRB identifications.

For prompt photo-z redshifts, the 2.2m GROND telescope (Greiner, these proceedings) has shown the way, with optical through nIR imaging in 7 bands with dichroics for prompt photo-z measures. Replicating GROND on even larger (4 - 8m) telescopes as a fixed Nasymth instrument, ideally with two such telescopes in both hemispheres at $\sim$180° separation (for $\sim$24h prompt coverage over the full sky). A step in this direction would be if semi-automatic queue scheduling could be done on telescopes such as Keck and Magellan. An optimum solution would be if four $\gtrsim$ 4m class telescopes could be dedicated to rapid photo-z and spectroscopy followup of GRBs (from *Swift* or successor missions) as well as optical-nIR transients discovered with LSST and VISTA, respectively. Prompt photo-z imaging and moderate and high resolution spectroscopy telescopes are *essential* to reap the science of both TDA, generally (particularly for LSST) and GRBs in particular. For the \$200M cost of one full EX-class Explorer mission, 4 such telescopes could now be built and operated. Discussions and planning in the US and international TDA communities should begin to explore this, in detail.

Alternatively, or in addition, a large telescope on "Dome A" in Antarctica would enable near-24h observational coverage (for DEC $\lesssim$ -10°) for $\sim$5-6 months/year during austral winter and with a cold (-80C !) mirror that would allow thermal background-limited imaging and followup spectroscopy out to $\sim 2.5\mu$m, which includes the "K-dark" band ($\sim$2.2 - 2.5μm) with minimal OH emission. A 3.5m telescope on Dome A is being considered by China in its next 5y Plan. Chinese astronomers have done extensive site testing at Dome A and report that photometric conditions at this 4080m site are possibly better than Mauna Kea (Zou et al 2010). Dome A has the advantage of better seeing and ground turbulence compared to the South Pole so that a telescope need "only" be located $\sim$10m above the surface ice rather than perhaps $\gtrsim$ 30m at the Pole. Dome A is undoubtedly the site for the closest terrestrial analog of a space-borne IRT. Although the devel-

Fig. 3. The *MIRAX-HXI* mission (4 upward-pointing coded aperture telescopes) scans half the sky every 96min orbit, while the 8 *EQUARS* instruments below scan the Earth.

opment and infrastructure costs will be significant, they are meager compared with putting even a 1m IRT in space and so should be pursued. We hope that eventually with a more enlightened Congress, the US will be able to resume science collaborations with China, but in the meantime those countries that can should investigate collaborative ventures with China for what may be the best high-z GRB IRT option for at least the coming decade.

Even if JWST is launched before the end of the decade, it will be "blind" without a sensitive wide-field GRB imaging mission that can provide few arcsec positions in what will likely be the post-*Swift* era (though obviously every effort should be made to keep *Swift* operating!). The French-Chinese SVOM mission will be a good interim mission for its now projected "post-2015" launch (Barrett 2011). With sensitivity down to 4 keV, *SVOM* will be more sensitive than *Swift*/BAT to GRBs with $E_{peak} \lesssim 30$keV as expected for high-z GRBs. The *SVOM* on-board 45cm visible telescope, with sensitivity given as $V \lesssim 23$, will alert ground-based telescopes for optical dropouts, but the $\gtrsim 30$ arcsec source positions will make nIR afterglows more difficult to identify among many potential candidates which themselves may not be in correspondingly deep JHK catalogs (unless VISTA or other wide-field nIR surveys have by then produced full-sky deeper catalogs).

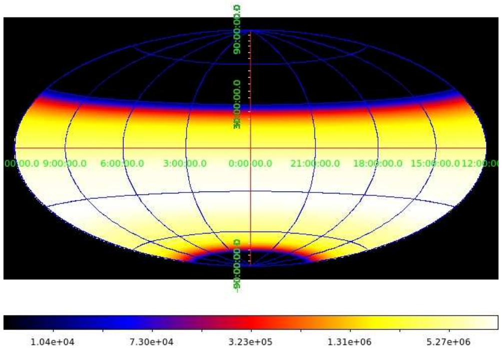

Fig. 4. The *MIRAX-HXI* 4-telescope total exposure (sec) per year in equatorial coordinates.

3. *MIRAX-HXI*: a proposed scanning TDA and sGRB mission

In addition to the *JANUS* and *Lobster* proposals for full GRB missions in the most recent Explorer proposal solicitation, *MIRAX-HXI* was submitted as a Mission of Opportunity (MoO) proposal (J. Grindlay, PI) to be the high resolution detector system for the imaging hard X-ray (5-200 keV) experiment on the *Lattes* satellite to be launched by Brazil in late 2016. *MIRAX-HXI* would conduct a sensitive survey of nearly the full southern sky (approximately $-80° \lesssim \mathrm{DEC} \lesssim +15°$), with 4 arcmin spatial resolution and $\lesssim 20$ arcsec ($\gtrsim 10\sigma$) source positions for both galactic and extragalactic transients as well as GRBs. Unfortunately, the proposal was also not accepted for Phase A study, but support from Brazil might be possible for the US-provided Hard X-ray Imager (HXI) detector planes for the 4 wide-field telescopes (each 25° x 25° , fully coded) and their support systems. A brief overview is given here of the mission, the detectors and sensitivities, followed by the science objectives enabled.

The *MIRAX-HXI* mission is particularly well-suited to provide $\lesssim 20$ arcsec positions for sGRBs from their prompt GRB emission (no afterglows and mission slews needed) that should enable followup optical identification and redshifts of ALIGO sources and, with a fu-

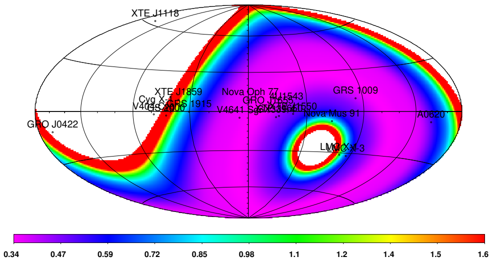

Fig. 5. The *MIRAX-HXI* 4-telescope 1 year sky coverage in galactic coordinates (with confirmed black hole X-ray binaries overplotted) and 5-150 keV sensitivity (mCrabs) for 1y survey.

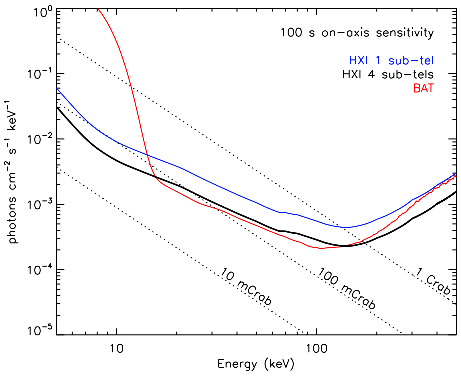

Fig. 6. Predicted *MIRAX-HXI* vs. *Swift*/BAT sensitivities.

ture(?) "super-LIGO", could realize the goal to use sGRBs for precision measures of the evolution of the Hubble constant with z, H(z).

3.1. MIRAX-HXI: mission & instruments

The MIRAX mission is planned as the first astronomical satellite from Brazil. Originally designed to have repeated pointings on the Galactic Center region to study both NS- and BH-accretion powered binary systems in the Galactic Bulge (Braga et al 2004), the spacecraft has been enlarged to accomodate two instruments (MIRAX and an Earth observing set of instruments, EQUARS) in a continuously *scanning* mission on the *Lattes* spacecraft (S/C), as depicted in Fig. 3. The *MIRAX-HXI* is a 2 x 2 array of coded mask telescopes mounted on the S/C with the axis of their combined 50° x 50° fully-coded FoV (60° x 60° FWHM) fixed-pointing 25° south of the orbital plane. The mission will be launched in an inclination i ~15° orbit so that over the ~50 day orbital precession period nearly 2/3 of the sky is covered. Every orbit provides nearly full southern sky coverage, with ~900 sec exposure on the Galactic Bulge and SgrA* as well as the South Galactic Pole, as shown in Figs. 4 and 5. Fig. 5 also shows the 5-150 keV sensitivity (mCrabs) for a 1y scanning total exposure.

The individual telescopes have smaller FoV and thus lower cosmic X-ray background (CXB) than the BAT telescope on *Swift*. The imaging detector plane for each telescope is 256 cm^2 of 8 x 8 close-tiled crystals of Cd-Zn-Te (CZT), each 2 x 2 x 0.5cm in dimension and each with 32 x 32 pixels (0.6mm pixel pitch). These are very similar to the fine-resolution imaging CZT detector arrays planned for the very much larger (4m^2 !) total area proposed for *EXIST*. The crucial element is the readout ASIC (directly bonded to each CZT crystal) which is the same as that developed at Caltech and now used for the 2 x 2 CZT detectors to read out the focal plane of each of the two focusing HX telescopes on the *NuSTAR* mission. By employing thicker graded passive shielding and having a lower CXB, the sensitivity over the 15-150 keV band is comparable in sensitivity to *Swift BAT* and a factor of $\gtrsim$ 2 better at $\gtrsim$ 400 keV for significantly better sGRB sensitivity. The major sensitivity increase over BAT, particularly for high-z GRBs but also X-ray binaries and AGN, is due to the HXI low energy threshold of 5 keV rather than 15 keV for BAT.

In fact, the sensitivity expected for *MIRAX-HXI* in the same band as *Swift*/BAT should be ~20-40% more sensitive than shown in Fig. 6 due to the scanning vs. pointing (even with small dither). This is because the scanning is continuously sampling all the detector pixels for both source and background counts whereas in fixed pointing, even with dithering, this is not the case. The BAT Slew Survey we have conducted (Copete et al 2011 in preparation) has demonstrated this scanning/pointing sensitivity ratio by processing scanning vs.

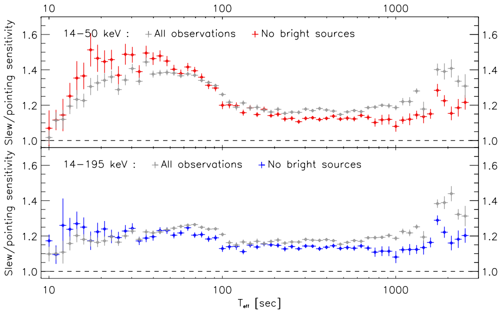

Fig. 7. BAT sensitivity ratio, Slew/Pointing, vs. exposure time and bright source contributions.

pointing BAT data on both blank sky fields and fields containing bright sources (e.g. Crab) and deriving sensitivities for each from both detector and image fluctuations. For the pointing data, the full BAT tools were used to correct for hot pixels and detector systematics; for the slew data, only hot pixel corrections were applied. The resulting sensitivity ratio vs. exposure time is shown in Fig. 7. It is clear that as originally proposed (Grindlay and Hong 2004), scanning improves coded aperture imaging sensitivity by averaging out systematic effects.

The *MIRAX-HXI* instrument and mission characteristics are given in Table 1.

3.2. *MIRAX-HXI* science goals & GRB probes

The continuous half-sky scanning with 4 arcmin resolution (3X finer than INTEGRAL and 5X finer than BAT) imaging over a significantly broader band proposed for *MIRAX-HXI* would represent a significant new capability for both Time Domain Astronomy (TDA) and GRB studies. Due to mass limitations on the *Lattes* S/C, the coded mask is thin (0.3mm, Tungsten) and so becomes increasingly transparent above 150-200 keV. However, for GRBs, the 5mm thick CZT detectors (vs. 2mm on BAT) will allow GRB spectra to be measured up to ~500 keV. Thus sGRBs are more efficiently detected than with BAT and should be closer to the ~1/3 fraction of all bursts as found with BATSE (Kouveliotou et al 1993) rather than the ~1/9 fraction detected with BAT. A wide range of science objectives are addressed by *MIRAX-HXI*, with three primary science goals:

1. Conduct a high sensitivity and resolution (spatial, temporal and spectral) survey of the Galactic Bulge and southern galactic plane to measure the populations of neutron star vs. black hole binaries as well as the first broad surveys for obscured BHs accreting from molecular clouds and for ^{44}Ti 68, 78 keV emission line sources in the full galactic plane that mark obscured young supernova remnants and constrain the Type II supernova rate in the Galaxy.
2. Conduct a unique TDA survey of the southern galactic plane as well as nearly half of the high latitude sky with the first high cadence (every 96min) and high duty cycle (15%) for each observation to measure both the physics and populations of time variable objects – from flaring red dwarf stars, to accretion disk outbursts of accreting NSs and BHs in binaries, to flaring blazars and new classes of AGN, and all with groundbased coverage from major TDA southern sky surveys such as LSST and ASKAP.
3. Conduct a GRB survey with significantly improved spectral bandwidth and resolution, prompt GRB localization, and both sensitivity and field of view extended by scanning, to enable new modes of identification of long GRBs that may be high-z events (with relatively soft E_{peak} values); and to be the first survey for sGRBs that yields both "precision" locations to enable optical host galaxy identifications without requiring (usually faint) afterglow detections that would provide EM detections and identifications of sGRBs in coincidence with ALIGO to measure H(z) and probe gravitational wave sources.

Additional details for *MIRAX-HXI* GRB science are discussed briefly here. From the sensitivities and FoV parameters given in Fig. 6 and Table 1, *MIRAX-HXI* should detect ~100 GRBs/y, or comparable to *Swift*/BAT, but with a much larger fraction of sGRBs. With $\lesssim 20$

Table 1. *MIRAX-HXI* instrument and mission parameters

telescopes & detectors:	2 x 2 coded aperture, 1000cm^2 imaging CZT
imaging energy band:	5 - 200 keV
GRB spectra band:	5 - 500 keV
field of view:	60° x 60° (FWHM); 50° x 50° fully coded
imaging resolution:	4' (FWHM)
source 90% conf. localization ($\gtrsim 5\sigma$):	~30"
typical GRB 90% conf. localization:	$\lesssim$ 20"
6 - 30 keV sensitivity, 1d, 1y:	8, 0.5 (x 10^{-11} cgs)
30 - 150 keV sensitivity, 1d, 1y:	10, 0.7 (x 10^{-11} cgs)
sGRB (50-250 keV) sensitivity, T90 =1s:	2 x 10^{-8} cgs
long GRB sensitivity, T90 =100s:	2 x 10^{-9} cgs
energy resolution (FWHM):	1.5 - 2.5 keV (5 - 200 keV)
HXI mass, power, telemetry:	95kg, 50W, 400kbs (continuous)
mission operation & duration:	continuous scanning, 4y
development of HXI & data proc.:	SAO/Harvard, GSFC, MIT, Berkeley, UCSD, Caltech
MIRAX structure, S/C, I&T, & mission ops:	INPE and AEB (Brazil)

arcsec positions (90% confidence radii) for a conservative $\gtrsim 10\sigma$ detection threshold, optical, nIR or radio counterparts can be found directly from this prompt GRB position, without relying on afterglow detections. This is possible for sGRBs, which have faint afterglows, with coincident ALIGO detections since these are limited to distances ~300 Mpc for NS-NS binary mergers. At that distance, a host galaxy with a NS-NS system either produced (and retained) in a globular cluster (Grindlay et al 2006) within ~100kpc of the host galaxy or instead produced by a double SN-II in a high mass binary in the galaxy and possibly ejected at ~300km/s over a merger timescale of ~1Gy and so also within ~100 kpc, would be within an angular offset of θ ~70arcsec. For a NS-BH merger, with larger GW luminosity and thus limiting distance ~600Mpc, the offset is expected to be $\lesssim$ 35 arcsec. Thus the HXI positional locations of $\lesssim$ 20arcsec should lead (in most cases) to unique host galaxy identifications, and thus redshifts, for sGRBs detected in coincidence with ALIGO.

For long GRBs at much larger redshifts, and in particular high-z GRB candidates with "soft" E_{peak} detections, the $\lesssim$ 20arcsec positions are of course not sufficient for unique host galaxy identifications without an optical or nIR afterglow. However the same prompt imaging and photo-z's invoked above for ground based detection would in fact identify the afterglow within these ~20 arcsec error circles nearly as easily as has been done with the ~3 arcsec circles from *Swift*/XRT. For long GRBs, the scanning *MIRAX-HXI* has an additional advantage over inertial pointing GRB telescopes apart from its added sensitivity (Fig. 7): for larger T90 values (as expected for a higher-z GRB), the scanning brings the source into higher coding fraction (and thus higher sensitivity detection) for GRBs that occur on the "entering FoV" side of the detector. Thus for ~half of GRBs with T90 $\gtrsim$ 300 sec, their detected S/N will increase as the ~900 sec scan duration (for any source to traverse the FoV) brings the source to higher coding fraction. Bursts near the "trailing edge" of the FoV are of course lost, but they would be less sensitive detections also in a pointed observation.

GRB image positions can be computed on board from rate triggers and could be brought down promptly via a commercial satellite phone link (e.g. IRIDIUM). The *Lattes* satellite carrying *MIRAX-HXI* could do followup pointings in a particularly urgent cases, but this is not part of the normal mission plan since there is no narrow field optical or soft X-ray telescope on the *Lattes* satellite. Pointings would also interfere with the continual scanning needed for the *EQUARS* Earth-observing instrument as well as for the expanded HXI survey coverage enabled by scanning in space and time. Hence the HXI detector is designed with spatial resolution that gives $\lesssim 20$ arcsec positions (for $\gtrsim 10\sigma$ source detections) as an instrument requirement that allows uninterrupted scanning and enables GRB (and all other sources) identifications from ground based facilities alone.

4. Conclusions

GRBs as probes of the high-z Universe will for the coming ~5y, at least, require new approaches for ground-based optical-nIR photo-z's to ensure prompt ($\lesssim$ 3h from trigger) detection of z $\gtrsim 8$ candidates. This could be done most easily with GROND-like multi-band (dichroic) imagers on $\gtrsim$ 2m telescopes, but ideally with 4 (2 in each hemisphere) $\gtrsim$ 4m telescopes with Nasymth foci for rapid response photo-z's followed by R $\gtrsim$ 100-3000 spectroscopy where possible. Nearly 24h coverage for ~5 months/y and near-space like conditions in the "K-dark" band could be obtained with a 3.5m IRT at Dome A in Antarctica, as is now being considered by China. Acquiring a sample of $\gtrsim$ 20 GRBs and redshifts (even just photo-z's) at z $\gtrsim 8$ is the highest priority, as this will provide unique constraints on SFR(z) during the EOR. But R ~3000 prompt spectroscopy is essential to actually *use* GRBs as probes of the Early Universe, by measurements of host galaxy metallicities and the shape of the red damping wing of Ly α to constrain the ionization fraction of the local IGM, all carried out in the first few hours while the afterglow is still bright. The proposed *MIRAX-HXI* instrument on the *Lattes* satellite to be launched by Brazil in late 2016, with its wide-field scanning and response extending down to 5 keV, can increase high-z GRB samples if there are the above-mentioned ground-based optical-nIR imaging and spectroscopy facilities for prompt followup.

For short GRBs, the relatively sparse (~10%) sample of sGRBs with *Swift* vs. the BATSE sample (~25%) means that more sensitive hard-response triggers are needed to maximize detections in the ALIGO era. The proposed *MIRAX-HXI* instrument on the *Lattes* satellite to be launched by Brazil in late 2016 would increase the rate of sGRB detections as well as provide $\lesssim$ 20arcsec prompt positions without the need for soft X-ray afterglow positions, which are relatively fainter and thus incomplete for sGRBs as detected with *Swift*. Thus a larger sample of sGRBs could be directly identified with possible host galaxies for those detected with ALIGO out to ~300-600Mpc, with rates dependent on still uncertain sGRB beaming factors, and (of course) that sGRBs are indeed due to NS-NS or NS-BH mergers. Obtaining $\gtrsim$ 10-20 such sGRB identifications and thus redshift vs. GW-chirp distances and will enable precision H(z) measures if GW detections can be extended out to larger distances.

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