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# Synergy between THESEUS and E-ELT

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**Abstract.** The Transient High Energy Sky and Early Universe Surveyor (THESEUS) is a space mission concept aimed at exploiting Gamma-Ray Bursts for investigating the early Universe and at providing a substantial advancement of multi-messenger and time-domain astrophysics. A fundamental contribution to achieve this goal will be provided by the powerful synergy between THESEUS and the extremely large ground-based telescopes which will operate in the next decade, like E-ELT. We discuss great improvements coming from this joint effort and describe some possible observing scenarios.

**Key words.** Gamma-ray: bursts – Cosmology: observations, dark ages, re-ionization, first stars – Multimessenger: gravitational wave, short GRBs, kilonova

## 1. Introduction

The driving science goals of THESEUS (Amati et al. 2018) aim at finding answers to multiple fundamental questions of modern cosmology and astrophysics, exploiting the mission unique capability to: a) explore the physical conditions of the Early Universe (the cosmic dawn and re-ionization era) by unveiling the Gamma-Ray Burst (GRB) population in the first billion years; b) perform an unprecedented deep monitoring of the soft X-ray transient Universe, thus providing a fundamental synergy with the next-generation of gravitational wave and neutrino detectors (multi-messenger astrophysics), as well as the large electromagnetic (EM) facilities of the next decade. Thanks to a perfect combination of its on-board instruments, THESEUS will be able to provide a detection of any class of GRB (long, short, X-ray flashes...), hugely increase the statistical sample of high-z GRBs (between 30 and 80 per year at z>6), detect, localize, and identify the electromagnetic counterparts to sources of gravitational radiation, which may be routinely detected in the late '20s / early '30s by next generation facilities like aLIGO/ aVirgo, KAGRA, Einstein Telescope and eLISA. These goals will be achieved also providing powerful synergies with the next-generation of extremely large multi-wavelength observatories (e.g., LSST, ELT, SKA, CTA, ATHENA) operating in the next decade.

In the following sections we discuss the possibility to establish a strong synergy with E-ELT, its first light instruments, presenting possible observational strategies and showing the reliability of such a cooperation and the compatibility with the queue scheduled observations of these large facilities.

## 2. A basic description of E-ELT + MAORY + MICADO system

The European Extremely Large Telescope (E-ELT) is a revolutionary scientific project for a 40m-class telescope that will allow us to address many of the most pressing unsolved questions about our Universe. The ELT will be the largest optical/near-infrared telescope in the world and will gather 13 times more light than the largest optical telescopes existing today. With its innovative five-mirror design that includes advanced Adaptive Optics (AO), the ELT will be able to correct for the atmospheric distortions (i.e., fully adaptive and diffraction-limited) from the start, providing exceptional image quality, 16 times sharper than those from the Hubble Space Telescope.

Multi Conjugate Adaptive Optics RelaY (MAORY) is the adaptive optic module that will be installed at the E-ELT at the first light of the telescope. It provides two different types of AO correction: a very high correction over a small FoV (diameter $\sim$ 10 arcsec), with performances rapidly degrading with distance from the bright natural star used to probe the wavefront (Single Conjugate Adaptive Optic – SCAO mode) and a moderate correction over a wide FoV (diameter $\sim$ 60 arcsec), with pretty homogeneous performances over the whole FoV (Multi Conjugate Adaptive Optic – MCAO mode). This will make possible to get AO assisted observations over a large fraction of the sky accessible from Cerro Armazones, meeting the system specification on Sky Coverage (SC $\geq$ 50% over the whole sky).

While MAORY must provide a port for a second instrument, still to be defined, its main goal is to feed the high-resolution NIR imager and spectrograph MICADO (Multi-AO Imaging Camera for Deep Observations), a workhorse instrument for E-ELT. The focal plane is equipped with 3×3 detectors. In imaging mode MICADO will provide an option with a wide FoV (50.4 $\times$ 50.4 arcsec$^2$) with pixel scale of 4mas/px and a high-resolution option with a 18.9 $\times$ 18.9 arcsec$^2$ FoV and a pixel scale of 1.5mas/px. Long-slit spectroscopy will be available with three different slit widths:

(a) 16 mas $\times$ 4 arcsec providing a spectral resolution R$\sim$8000 for sources filling the slit and 11000 < R < 18000, depending on wavelength, for point sources within the slit;
(b) 48 mas $\times$ 4 arcsec providing R$\sim$2500 for extended sources filling the slit;
(c) 20 mas $\times$ 20 arcsec with a resolution R$\sim$6000 (when filled) specifically suited to observe galaxy nuclei, to include sky simultaneously at larger off- axis distances. This slit is available for the K-band only. An option on the order sorting filter will allow access to two different spectral ranges 0.8 –1.45 $\mu$m (IzJ passbands simultaneously) and 1.45–2.4 $\mu$m (HK passbands simultaneously). The pixel scale will always be 4 mas.

The science cases concerning GRB science (reported in Sect. 3 and 4) are widely described in the MAORY Science cases White Book (Fiorentino et al. 2017) together with a detailed observational strategy. In this paper we point out the benefit of having a strong synergy between THESEUS and E-ELT.

## 3. Exploring the early Universe with Gamma-Ray Bursts

Gamma-ray bursts (GRBs) are bright flashes of high-energy radiation. They are so luminous to be detected up to very high redshifts. By using their brightness and their association with star forming regions within galaxies it is possible to shed light on the high redshift Universe. We will consider the long GRBs (LGRBs),i.e. GRBs with $T_{90}$ > 2s associated with the death of massive stars. These major stellar explosions are unique powerful tracers of the star formation rate (SFR) up to z$\sim$10–12, may be signatures of pop-III stars. Detectable up to z $\sim$10–12 thanks to their huge X/gamma-ray luminosities, absorption spectroscopy of the fading NIR afterglow emission and deep imaging (and possible emission spectroscopy) of their host galaxies can be used to explore the re-ionization era, to measure the cosmic star-formation rate, the number density and properties of low-mass galaxies, the neutral hydrogen fraction, the escape fraction of UV photons, the cosmic chemical evolution.

The synergy between the extremely large ground-based telescopes available in the '20s like E-ELT+MAORY+MICADO and the future foreseen high-energy satellites devoted to the GRBs science like the THESEUS mission proposed for ESA call M5, will provide redshifts and luminosities that are essential to optimise the time-critical follow-up (Yuan et al. 2016). Thanks to this strategy, the selection of the highest priority targets will be possible for the most appropriate observational strategy. The present detection rate of GRBs at z > 6 is about 0.7–0.8 /year, thanks to, and limited by, the Swift satellite capabilities and follow-up possibilities with ground and space facilities. This rate will likely increase to ∼2–4 / year at the beginning of the next decade, thanks to next generation space facilities like SVOM and EP (Einstein Probe), and may grow up to several tens of events per year at the end of the '20s if THESEUS, or an analogue mission concept, will be selected and realized by ESA of other space agencies.

We intend to observe both afterglows (AG) and host galaxies (HG) by performing deep imaging and spectroscopy with E-ELT+MAO RY+MICADO of a number of high redshift GRBs (z>6) triggered and followed-up in the first phases by THESEUS. These observations will be able to address key questions described in the following and can be crucial to fully characterize the properties of star-forming galaxies over the whole cosmic history.

### 3.1. The Lyman continuum escape fraction

High-S/N afterglow spectroscopy reveals the neutral hydrogen column along line-of-sight to the GRB, providing a powerful alternative to the lack of direct observations of escaping Lyman continuum radiation at z > 6, especially for the small galaxies responsible for the bulk of star formation. Since the opacity of the medium to far ultraviolet (FUV) photons depends on this column, a statistical sample of afterglows can be used to infer the average escape fraction ($f_{esc}$) over many lines of sight, specifically to the locations of massive stars dominating global ionizing radiation production (Figure 1). Useful constraints have so far only been possible at z = 2–4, indicating an upper limit of $f_{esc}$ <7.5% (Fynbo et al. 2009). Future observations of the AG of GRBs at z > 6, particularly in the era of 40 m ground based telescopes like E-ELT+MAORY+MICADO, will provide much more precise constraints on the epoch of reionization.

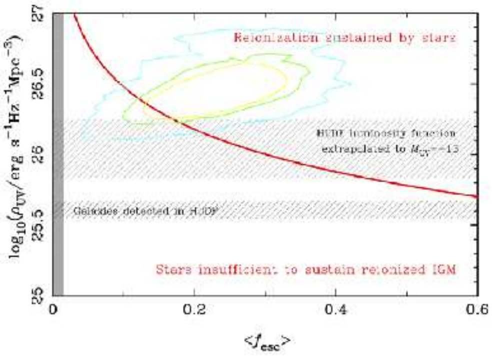


**Fig. 1.** The UV luminosity density from stars at z∼8 and average escape fraction $< f_{esc} >$ are insufficient to sustain reionization unless the galaxy luminosity function steepens to magnitudes fainter than $M_{UV}$=−13 (grey hatched region), and/or $< f_{esc} >$ is much higher than that typically found at z∼3 (grey shaded region). Even in the late 2020s, $< f_{esc} >$ at these redshifts will be largely unconstrained by direct observations. Shown are 2-$\sigma$ contours for the cases of 10 (cyan), 25 (green) and 40 (yellow) GRBs in range z=7-9 with deep spectroscopic follow-up and host searches. The input parameters were $\log_{10}(\rho_{UV})$=26.44 and $< f_{esc} > \geq 0.23$, close to the (red) borderline for maintaining reionization by stars.

### 3.2. The build-up of metals, molecules and dust

Bright GRB afterglows with their intrinsic power-law spectra provide ideal backlights for

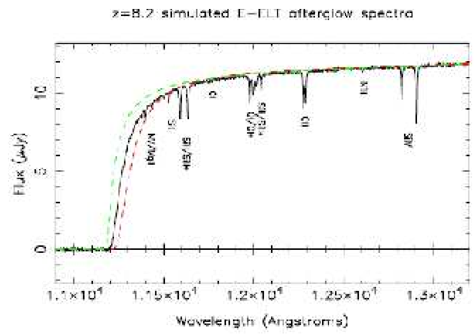


**Fig. 2.** Simulated ELT 30 min spectrum of a faint GRB afterglow observed after ∼1 day. The S/N provides abundance determinations from metal absorption lines, while fitting the Lyman-$\alpha$ damping wing simultaneously fixes the IGM neutral fraction and the host HI column density, as illustrated by the two extreme models, a pure 100% neutral IGM (green) and best-fit host absorption with a fully ionized IGM (red).

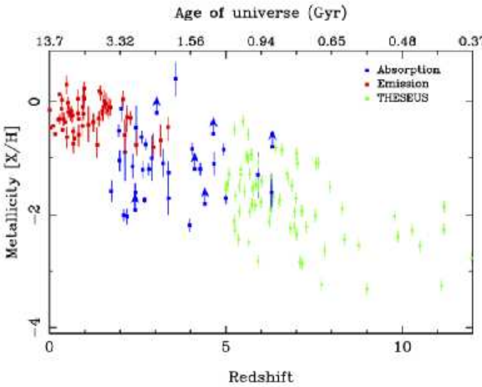


**Fig. 3.** We have simulated a sample of z>5 THESEUS discovered pop-II GRBs with deep spectroscopic follow-up, and a plausible spread in metallicities and precision of determination. The metallicity distribution at z∼7 is set here to match that from the simulations of (Cen et al. 2014) with a linear decline of average [X/H] with redshift above that. The numbers of event correspond to the minimum numbers expected from our simulations.

measuring not only the hydrogen column, but also obtaining abundances and gas kinematics probing to the hearts of their host galaxies (Hartoog et al. 2015). In addition, the imprint of the local dust law, and the possible detection of $H_2$ molecular absorption, provides further detailed evidence of the state of the host interstellar medium (ISM) (Friis et al. 2015). Thus they can be used to monitor cosmic metal enrichment and chemical evolution to early times, and search for evidence of the nucleosynthetic products of even early generations of stars (Pop-III). Thanks to E-ELT+MAORY+MICADO spectra, abundance determinations will be possible through simultaneous measurement of metal absorption lines and modelling the red-wing of Lyman-$\alpha$ to determine host HI column density, potentially even many days post-burst (Figure 2). As can be seen, the combination of the unique capabilities of THESEUS with the excellent sensitivity and spectroscopic performances of these future facilities would allow an unprecedented study and comparison of the average composition of the host galaxy and of the circumburst environment (Figure 3).

### 3.3. *Topology of reionization*

One of the last uncharted astrophysical epochs is the time between recombination and the end of the first phase of star formation. Massive stars, possible progenitors of LGRBs, are likely to be a significant contributor to the ionizing photons at high redshift, thus GRBs are expected to occur also during the reionization epoch. Unlike luminous QSOs which ionize the intergalactic medium around themselves, GRBs do not suffer from the "proximity effect" (Fan et al. 2006). This makes GRBs cleaner probes of the Gunn-Peterson absorption used to estimate the degree of ambient ionization. With high-S/N afterglow spectroscopy the Lyman-$\alpha$ red damping wing can be decomposed into contributions due to the host galaxy and the intergalactic medium (IGM). The latter provides the hydrogen neutral fraction and so measures the progress of reionization local to the burst. With samples of few tens of GRBs at high redshift, we can begin to statistically investigate the average and variance of the reionization process as a function of redshift (McQuinn et al. 2008).

### 3.4. Population III stars

The multiwavelength properties of GRBs with a Pop-III progenitor are only predicted on the expected large masses, zero metallicity of these stars. Even the detection of a single GRB from a Pop-III progenitor would put fundamental constraints on the unknown properties of the first stars.

### 3.5. High redshift star formation induced by galaxy interactions

Nearby absorbers have already been identified in the spectrum of particularly bright GRB afterglows. They indicate possible galaxy interaction which triggers star formation (SF), and are more frequent at high redshift. The fraction of absorbers in the spectra of GRB afterglows is ~5 times larger than in QSO spectra. Thus GRBs are a better tool to understand the bound between galaxy interaction and star formation in the high redshift Universe. We intend to exploit the high angular resolution and sensitivity achievable with E-ELT+MAORY+MICADO for both imaging and spectroscopy to study the morphological properties and the UV emission of the host of high-z GRBs triggered by THESEUS which show two strong nearby absorbers in the AG spectrum. These observations will allow us to test the hypothesis that galaxy interactions at high redshift induce the formation of very massive stars and GRB progenitors.

### 3.6. HG search

Even to the depth achieved in the Hubble Ultra-deep Field (HUDF), we only know that the faint-end of the luminosity function (LF) at z > 6 approaches a power-law of slope $\alpha$ = 2, with an unconstrained cut-off at low luminosities, which affects the total luminosity integral. Although currently limited by small-number statistics, early application of this technique has confirmed that the majority of star formation at z~6 occurred in galaxies below the effective detection limit of HST (Tanvir et al. 2012; McGuire et al. 2016). Since the exact position and redshift of the galaxy is known via the GRB afterglow, GRB hosts search and observations are more efficient than equivalent deep field searches for Lyman-break galaxies. We thus consider fundamental to conduct deep searches with E-ELT+MAORY+MICADO for the hosts of GRBs at high-z in order to derive the LF at z >6.

## 4. Characterization of EM counterpart of multi-messenger compact binary coalescence systems

The launch of THESEUS will coincide with a golden era of multi-messenger astronomy. With the first detection of gravitational waves (GWs) by Advanced detectors (Abbott et al. 2016a,b) a new window on the Universe has been opened. Several of the most powerful transient sources of GWs predicted by general relativity, e.g. binary neutron star (NS- NS) or NS-black hole (BH) mergers are expected to be associated with bright electromagnetic (EM) counterpart signals across the entire EM spectrum and in particular in the X-ray and gamma-ray energy bands, as well as neutrinos. They are thought to be the progenitors of short gamma-ray bursts (SGRBs) and kilonova/macronova transients. On August 17, 2017 the merger of two compact objects with masses consistent with two neutron stars was discovered through gravitational-wave (GW170817), gamma-ray (GRB170817A), and optical (SSS17a/AT 2017gfo) observations (Abbott et al. 2017a,b; Pian et al. 2017). In the new era of gravitational-wave astronomy, THESEUS aims at playing a fundamental role in multi-messenger and time-domain astrophysics, operating in strong synergy with future major ground-based telescopes, like E-ELT.

Shot GRBs (SGRBs) are identified as those GRBs with duration ($T_{90}$) less than about two seconds and with harder spectra with respect to the more frequent long GRBs (Kouveliotou et al. 1993). The study of their afterglows and host galaxies provides critical information about their explosion properties and progenitors. Observations carried out in the last decade show that these events, occurring in both early and late-type galaxies, are associated to relatively old ($\geq$ 50 Myr) stellar populations, and do not show evidence of associated supernovae. In addition, SGRBs have systematically larger offsets from their host galaxies centers than LGRBs, in line with the idea of different progenitors. Indeed, one of the key predictions of the compact object merger model is that systemic natal kicks may lead to substantial offsets between the birth and explosion sites of these systems (Fryer et al. 1998, 2004). Observationally, some short GRBs at such large offsets can appear to be host-less because their projected locations will extend much beyond the visible extent of typical galaxies. The distribution of natal kick velocities of compact objects and compact object binaries is still an open issue, ranging from typical velocities of few hundred km/s (Hobbs et al. 2005) to less than $\sim$30 km/s in the vast majority of the systems (Beniamini et al. 2016). Besides, dynamical kicks, due to close gravitational encounters, are also expected to contribute to the ejection of compact object binaries from their birthplace (Mapelli et al. 2011). For these reasons, it is crucial to assess the impact of natal kicks and dynamics on SGRBs. In particular, it is important to establish that the claimed host-less GRBs do not in fact lie on top of very faint system, hitherto undetected, e.g. the very faint host galaxy of GRB 070707 (Piranomonte et al. 2008).

Another predicted, and recently detected as said above, electromagnetic signature of NS-NS/NS-BH binary mergers is the so-called “kilonova” (KN). Hydrodynamical simulations have shown that, around $10^{-4}$–$10^{-2}$ $M_{\odot}$ of material may become tidally unbound and expelled (Rosswog et al. 2005). This material will assemble into heavy elements via r-process. Kilonova emission is thought to originate from the radioactive decay of these newly formed r-process elements (Li et al. 1998). Computations of the opacities connected to r-process material indicate that the bulk of kilonova emission is expected to peak in the NIR on a timescale of a few days (Kasen et al. 2013; Grossman et al. 2013; Tanaka et al. 2013). The colour and brightness of kilonova light curves are therefore sensitive markers of the ejecta composition, and can be used to gain insight into the nature and the physics of compact object mergers (Kawaguchi et al. 2016; Kasen et al. 2015). Kilonova emission is predicted to be isotropic and for this reason it is a promising electromagnetic counterpart of the merging of NS-NS/NS-BH systems, alternatively to the beamed SGRBs for which the chances of a joint GW-SGRB detection are rather low (Ghirlanda et al. 2016). A kilonova counterpart is thus expected to be found among the transient sources discovered in the GW-localized sky regions (after the detection of a NS-NS/NS-BH GW event) or identified as an emerging NIR component from the rapidly decaying afterglow emission of short GRBs, as it has been done in the case of GRB-GW 170817 thanks to the quasi simultaneous detection of GW and SGRB.

Thanks to the synergy with THESEUS we intend to exploit the unprecedented spatial resolution and sensitivity of ELT+MAORY+MICADO to perform observations to shed light on the EM counterparts of NS-NS and NS-BH binary systems. A possible strategy to this aim is to perform deep observations to search and characterize the faint host galaxies of SGRBs and “late” ToOs (1-10 days after the burst) to detect the kilonova emission.

### 4.1. Search for kilonova emission

Until August 2017, the association between SGRB and kilonova emission relied only on few cases. Indeed the near-IR excess detected with HST observations following the SGRB 130603B (Tanvir et al. 2013) was interpreted as kilonova emission and the first direct evidence that SGRBs originate from NS-NS/NS-BH mergers. Late-time optical and near-IR observations place limits on the luminosity of optical and near-IR kilonova emission following this SGRB of $\sim$ few $\times$ $10^{40}$ erg s$^{-1}$ (Fong et al. 2016). Other two suggestive pieces of evidence for SGRB/KN association has been proposed for SGRB 050709 and SGRB 060614 (Yang et al. 2015; Jin et al. 2015, 2016). As discussed above, the outstanding case of GW170817/GRB170817A provided a fundamental confirmation of this picture. The synergy between THESEUS and extremely large telescopes of the future like E-ELT will allow a sistematic study and deep understanding of the connection and interplay between the NS-NS merging and SGRBs and KN phenomena. Given current kilonova models, deep optical and near-IR AG observations at 1-10 days after a SGRB to depths of ∼23-24 ABmag, up to about 200 Mpc, (i.e. the detection limit of second generation GW detectors) are necessary to probe a meaningful range of parameter space (Figure 4). This highlights the key role of instruments like E-ELT+MAORY+MICADO in performing meaningful searches for EM counterparts to gravitational wave sources, through the dual possibility of looking for KN evidence in the SGRB NIR-afterglows or, alternatively, among the EM candidates found in the 1-10 deg$^2$ sky regions of GW-localized NS-NS/NS-BH mergers, that will be followed-up as soon as their position will be available via GCN or ATel.

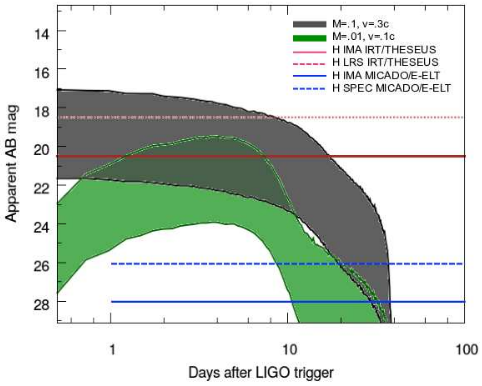


**Fig. 4.** Theoretical H-band lightcurves of kilonova based on models (Barnes et al. 2016). The lightcurves are in observer frame for a source between 50 and 400 Mpc. Gray model is for the most optimistic case of a kilonova with 0.1 $M_\odot$ ejected mass with speed of 0.3 c. Green model is for a weaker emission, corresponding to 0.01 $M_\odot$ ejected mass with speed of 0.1 c. The continuous and dashed red lines indicate the THESEUS/IRT limiting H magnitudes for imaging and prism spectroscopy, respectively, with 300 s of exposure (Amati et al. 2018). The continuous and dashed blue lines indicate the ELT/MICADO H-band limiting magnitudes for imaging and spectroscopy, respectively.

### 4.2. Deep observations to characterize the host galaxies of SGRBs

NS-NS/BH mergers are expected to be found in the most massive galaxies, but the way the progenitor was born can also play a role. In particular, one should also consider the conditions that lead to the episode of star formation that generated the stellar population which the progenitor belongs to (Leibler et al. 2010; Fong et al. 2013). Indeed, different channels for the formation of the progenitors lead to different star formation histories, and thus morphology and contribution of the star clusters. Moreover, one of the main uncertainties on the SGRB progenitors is the time between the progenitor formation and the GRB explosion (delay-time). Thus, by constraining the age of the host stellar population, it is possible to get a reliable indication on the age of the progenitor. A first explorative study on a sample of SGRB host galaxies has been carried out with HST, providing constraints on their offsets and on how their locations track the host galaxy light distribution (Fong et al. 2010). However, up to now studies of the mass and age refer to the whole host galaxy, since the angular resolution (considering the redshift z∼0.5-1) of the available facilities is not sufficient to measure age and mass of the multiple stellar components in the hosts. The high angular resolution and high sensitivity of MAORY+MICADO will allow us to resolve the morphology of the handful of SGRB hosts located at redshift z<0.2. Thus, we can study in detail any relation between the SGRB site explosion and the surrounding environments and estimate the mass and absolute age of star clusters that we will identify (Bono et al. 2010).

### 4.3. Deep observations in the region of host-less SGRBs to search for faint host galaxies

The short GRB offsets normalized by host-galaxy size are larger than those of long GRBs, core-collapse SNe, and Type Ia SNe, with only 20% located at ≤1 $r_e$ ($r_e$ being the galaxy effective radius, which accounts for the range of HG sizes and any systematic trends in these sizes between the various GRB and SN populations) and about 20% located at ≥5 $r_e$. The inferred kick velocities are ~ 20-140 km $s^{-1}$, which is in reasonable agreement with Galactic NS-NS binaries and population synthesis models. About 20% of well localized SGRBs (~7% of the total number of SGRBs) have been classified as host-less (Fong et al. 2013). Several galaxies are present in the deep optical-NIR HST images of the region of these "host-less" SGRBs, but they sometimes have a high probability of chance coincidence because of non-optimal X-ray localization precision (2-3 arcsec). Thus, these galaxies cannot be identified as hosts of these events. In this context a possible strategy may first consider a small sample of few (<10) accurately localized (via radio and/or optical afterglow detection) host-less SGRBs and investigate if these might be inside very faint galaxies or may have been ejected by natal kicks or dynamics. Distinguishing between these two scenarios gives constraints on the formation of NS binaries.

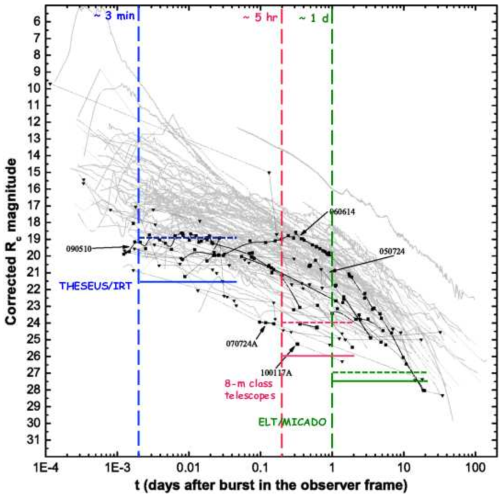


**Fig. 5.** A large sample of observed R band lightcurves of long and short GRBs are shown. Highlighted (black lines with circles, squares and triangles) are the short GRB curves, in grey the long GRB ones. Data is corrected for Galactic extinction. Adapted from Kann et al. (2017). The limiting magnitudes achievable with THESEUS/IRT (blue lines), 8-m class telescopes (red lines) and ELT/MICADO (green lines) are also shown. Dashed line for the spectroscopy, solid line for the imaging. The magnitudes are rescaled from H-band to R-band assuming achromatic behaviour and a spectral index $\beta$=0.7. A tentative observation strategy could consist of the following steps: first starting the follow up with IRT, then activating the observations with 8-m class telescopes after few hours, finally, according to the brightness of the afterglow and thanks to the very high sensitivity of ELT, performing late observations for weeks.

## 5. Possible observational strategy with E-ELT+MAORY+MICADO

The number of GRBs at z>8 is expected to not exceed 10/year. Following-up 10 GRB/year with the major telescopes that will be available in the '30s (e.g. ELT, GMT and TMT and hopefully JWST) seems reliable. For 6<z<8, "smaller" telescopes (e.g., existing facilities like VLT) may be used, which will have more observing time available, thus allowing to follow tens of GRBs/year (Figure 5). To follow-up high-z GRBs with the major telescopes (e.g., ELT) we consider the Target of Opportunity (ToO) policy already widely applied at VLT or similar telescope. Due to their high performances, it is sufficient to ask for late ToO even or more than 1 day after the burst to have exquisite dataset anyway. However, note that all of the next generation ground based facilities, have requirements for rapid response of 30 minutes or less, similar to the rapid response mode (RRM) used at ESO/VLT. Alerts sent to the observatory can be acted upon rapidly via automated processes or on timescales as short as several minutes by the observing assistants. Some integrated fraction of time, possibly even as high as 10% to 20%, will be allotted for ToO programs but the intermissions could occur at anytime during queue scheduled observations. If we assume that z~8 afterglows have IR brightness and evolution similar to those observed up to now, the faintest afterglow will have H(AB)~26 at 2 hrs after the GRB (applying redshift correction to Kann et al. 2017; Figure 5). An afterglow with average brightness observed ~1 day after the GRB will have similar brightness, too. Using ELT equipped with the instruments foreseen for its first light (MICADO and HARMONI with Adaptive Optic Correction provided by MAORY), it is possible to detect spectroscopically (S/N>3) an afterglow with H(AB)~26 with less than 1 hr exposure time. Similarly, considering very faint host galaxies with H(AB)~29 (Savaglio et al. 2009) will be well detected with ELT in imaging with ~1 hr exposure time.

We report below, as examples, the set-up of observing strategy for E-ELT+MICADO+MAORY for each of the cases discussed above. Note that the estimates of the exposure times have been obtained with the ESO-ELT ETC, and all the input parameters are specified in the MAORY White Book (Fiorentino et al. 2017).

### *5.1. Early Universe*

A possible strategy may be to perform the follow-up of the AGs and deep observations of the HGs for a number of high redshift GRBs (z>6). Deep imaging and spectroscopy with E-ELT+MAORY+MICADO can allow to fully characterize the properties of star-forming galaxies over the whole cosmic history.

#### Afterglow follow up - request for ToO

**MICADO Pixel Scale/Fov:** Small field (1.5mas/px, 20″FoV) motivated by the small size of the actual targets.
**MICADO Observation mode:** Standard Spectroscopy MICADO
**Spectral set-up:** Slit 1, 16 mas × 4 arcsec, spectral coverage: IzJ+HK.
**Estimate Number of Images/Epochs:** Since 2020 the expected rate of GRBs at z>6 is >5 per year. Considering visibility constraints, we expect to have ~2-3 targets/yr.
**Average Integration time per image (magnitude of targets; S/N required):** Assuming for the spectrum an AG at z=10, with H~26 we need ~1.5hr exposure time to reach S/N~3.
**SCAO vs. MCAO:** MCAO is the only viable mode as the circumstance of a target within ~10″ of a bright star (allowing SCAO) is rare or non-existing.
**Synergies with other facilities:** Target positions will be provided by high-energy satellites available at that time (maybe Swift, SVOM, THESEUS) combined with accurate afterglow localizations.
**Acquisition:** our targets are point sources so 20″ FoV will be selected.
**Any other comment:** Quick response to the activations.

#### Host galaxies observations

**MICADO Pixel Scale/Fov:** Small field (1.5mas/px, 20″ FoV).
**MICADO Observation mode:** Standard Imaging and Spectroscopy
**MICADO Spectral set-up:** slit 2, 50mas × 4arcsec, spectral coverage IzJ+HK. Slit with adjustable orientation would enhance the scientific return (e.g. AG+HG).
**Filters required:** J, K plus an additional filter according to the redshift
**Estimate Number of Images/Epochs:** At present the sample of GRB's HGs at z>6 is limited to 9 events. In the late 20′s the expected rate of GRBs at z>6 is >5 per year. We expect to have ~2-3 targets/yr (according to visibility constraints).
**Average Integration time per image (magnitude of targets; S/N required):** Worst case for the imaging of an HG at K=30, with ~4 hr exposure time a S/N~3 is reached. If the HG is brighter than K~26, a 2.5hr spectrum (low resolution) is needed to reach S/N>5.
**SCAO vs. MCAO:** MCAO is the only viable mode as the circumstance of a target within ~10″ of a bright star (allowing SCAO) is rare or non-existing.
**Comparison with JWST:** Spatial resolution is the key issue here: ELT+MAORY+MICADO is much better than JWST by a factor of >3, at high SR, comparing MICADO observations in H band to JWST observations in I band.
**Synergies with other facilities:** Target positions will be provided by high-energy satellites available at that time and/or optical telescopes (maybe Swift, SVOM, THESEUS)

**Acquisition:** the characteristic size of GRB HG is ~1 arcsec. No problem in getting a useful pointing within the 20″ FoV.

### 5.2. Multimessenger science

We intend to exploit the unprecedented spatial resolution and sensitivity of E-ELT +MAORY+MICADO to perform observations to shed light on the EM counterparts of NS-NS and NS-BH binary systems. In the following tentative observational strategies we suggest to perform deep imaging and spectroscopy to search and characterize the faint host galaxies of SGRBs and "late" ToOs (1-10 days after the burst) to detect the kilonova emission.

#### Request for late ToO to search kilonova emission

**MICADO Pixel Scale/Fov:** Small field (1.5mas/px, 20″ FoV) motivated by the small size of the actual targets.
**MICADO Observation mode:** Standard Imaging and Spectroscopy
**MICADO Spectral set-up:** slit 1 (16 mas × 4 arcsec), IzJ+HK Filters required: I, H. The kN emission is best characterized comparing lightcurves obtained with two bands separated in wavelength to test the color evolution; thus, we ask for I and H band (due to the better sensitivity of the instrument in this filter with respect to the K one).
**Estimate Number of Images/Epochs:** uncertain rate of NS- NS, NS-BH merging systems (~few tens/year). Considering well-localized SGRBs at z<1 and/or kN candidates from GW trigger, we expect ~3 similar targets/yr. Strategy for each event: photometric monitoring (I, H filters) of 10 epochs with 2 days cadence starting from T0+2days and spectral acquisition for brightest events (I<24).
**Average Integration time per image (magnitude of targets; S/N required):** For S/N~10, I=28, and H=25 are reached with integration time of 10 min and 15 s respectively. For the spectrum, with I<24 less than 2 hr exposure time are needed to reach S/N~10.
**SCAO vs. MCAO:** the circumstances of a target within ~10″ of a bright star (allowing SCAO) should be considered in order to select SCAO or MCAO mode.
**Synergies with other facilities:** high-energy satellites available at that time (maybe Swift, SVOM, THESEUS), optical telescopes, ground-based GW detectors.

#### SGRBs with confirmed host galaxies

**MICADO Pixel Scale/Fov:** Small (1.5mas/px, 20″ FoV) or Large (5mas/px, 50″x50″ FoV) field, depending on the size of the galaxy.
**MICADO Observation mode:** Standard Imaging
**Filters required:** J, K to characterize the mass and age of the star clusters within the host galaxy
**Estimate Number of Images/Epochs:** 2004-2016 → 5 HGs at z<0.2 (about 20% of the total SGRBs with measured redshift) 2 images/1 epoch per object.
**Average Integration time per image (magnitude of targets; S/N required):** We reach K~30.5 mag with 2.5 hr exposure time at S/N~3 (to resolve faint star cluster inside the close SGRBs HGs) The half-light radii of the targets are < 10 pc at z=0.2 → ~point sources.
**SCAO vs. MCAO:** MCAO is the only viable mode as the circumstance of a target within ~10″ of a bright star (allowing SCAO) is unlikely.
**Synergies with other facilities:** Targets positions and integrated magnitudes/colors from SGRBs detection with high-energy satellites available at that time (maybe Swift, SVOM, THESEUS) combined with accurate afterglow localizations.
**Acquisition:** size of GRB HG >1 arcsec, → useful pointing within the 20″ FoV and 50″×50″ FoV, depending on the size of the galaxy
**Any other comment:** possibility to observe the most peculiar targets, in spectroscopic mode with HARMONI/ JWST

### Confirmed hosts-less SGRBs - search for their faint galaxies

**MICADO Pixel Scale/Fov:** Small field (1.5mas/px, 20″ FoV)
**MICADO Observation mode:** Standard Imaging
**Filters required:** K
**Estimate Number of Images/Epochs:** 2004-2016 → 6 host-less SGRBs and 6 "inconclusive" HGs (Fong et al. 2013). By 2024 (7 years from now) we expect a sample of∼12 targets. We request 1 images/1 epoch per object.
**Average Integration time per image (magnitude of targets; S/N required):** Considering limiting magnitude for the host-less of K∼25, it is possible to reach S/N∼5 with 1.8 hr exposure time. Estimates obtained with the ESO-ELT ETC, input parameters are specified in the WB.
**SCAO vs. MCAO:** the circumstances of a target within ∼1″ of a bright star (allowing SCAO) should be considered in order to select SCAO or MCAO mode.
**Synergies with other facilities:** Targets positions from SGRBs detection with high-energy satellites available at that time (maybe Swift, SVOM, THESEUS) combined with accurate AG localizations. Some targets can be observed in spectroscopic mode with HARMONI/JWST depending on the brightness.
**Acquisition:** the characteristic size of putative host galaxy (likely above z∼1) is expected to be well within 20″ FoV. Finding charts available.
**Any other comment:** If any host galaxy will be found, spectrum will be possibly requested.

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