The TOROS project

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1 Searching for Optical counterparts of Gravitational Wave Sources

The first direct detection of gravitational waves (GW) may be possible with the Advanced Laser Interferometer Gravitational wave Observatory (aLIGO) and similar facilities within a few years. Binary neutron star (NS) mergers are expected to be among the most numerous and strongest GW sources [1].

The coalescence and merger of a neutron-star–neutron-star (NS-NS) or neutron-star–black-hole (NS-BH) binary is among the most energetic events in the Universe and has long been proposed as the process leading to short-hard gamma-ray bursts (SGRBs) [2, 3]. NS-NS and NS-BH mergers are also some of the most promising candidates for producing gravitational-wave (GW) signals, detectable out to ~ 300 Mpc. Additionally it has been predicted [4, 5, 6] that the merger of NS-NS or NS-BH binaries should have an associated optical transient called a “macronova” or “kilonova”, powered by the radioactive decay of heavy nuclei synthesized in the merger ejecta through rapid neutron capture. It is also speculated that this mechanism may be the predominant source of stable r-process elements in the Universe (e.g., [7, 8]). These optical events are expected to have relatively low luminosities, with most of their emission at red and near-infrared wavelengths, and to last for a few days.

Recently reported optical and near-infrared observations of the transient associated with the short-duration gamma-ray burst GRB130603B [9, 10] exhibit the signatures predicted by “kilonova” models, indicating that this event could indeed confirm that compact-object mergers are the source of SGRBs. Kilonovae could then offer an alternative, unbeamed electromagnetic signature of the most promising sources for direct detection of gravitational waves. Simultaneous detection of electromagnetic signals associated with gravitational events seen by aLIGO and AdVIRGO could thus provide gravitational wave astronomers with crucial complementary information about these systems that is not directly accessible via gravitational waves.

But one key problem to consider is the following: GW detectors are all-sky detectors that allow localization via triangulation. They generally have poor pointing accuracy even for high signal-to-noise ratio events, leading to uncertainties of up to a few hundred square degrees in the target area for electromagnetic followup. Therefore, wide-field cameras and rapid follow-up observations will be crucial for the first EM counterpart detection. High quality, resolution and deep wide-field images are other crucial ingredients, which means that facilities with telescopes dedicated to the EM follow-up should be constructed at optimal locations.

In 2011, scientists from several European and North and South American institutions established a collaboration to develop such a facility, and called the project TOROS: Transient Optical Robotic Observatory of the South[1]. In addition to the general scientific motivation outlined in the previous section, we were driven by the limited number of southern facilities with wide fields of view that would be capable of dedicated searches for aLIGO and adVIRGO released triggers during their first years of operation.

We decided that Cordón Macón, a mountain range in the province of Salta, Argentina (W67°19′41.6”, S24°37′21.9”, 4637m elev.) offered a unique opportunity for the development of a new astronomical facility. This site was first considered as a location to develop an astronomical facility by the European Southern Observatory, as part of their search for suitable locations for the European Extremely Large Telescope (E-ELT)[2].

2 TOROS characteristics

TOROS will have a primary mirror diameter of 0.6 m, a field-of-view of 9.85 sq.deg. and a very broad bandpass ($0.4 - 0.9$ μm, equivalent to a combination of the Sloan *griz* filters). It will be a fully robotic facility, driven by a priority-based intelligent agent/scheduler with four modes of operation in decreasing order of priority: (1) follow up of gravitational-wave triggers; (2) follow up of γ-ray burst triggers from *Fermi*, *Swift* and other missions; (3) baseline imaging of the entire surveyable area; (4) search for short-duration transient events, variable sources and moving objects within the DES and VISTA-VIKING fields.

With TOROS, we expect to build a robust survey system that maximizes the probability of detecting the electromagnetic counterparts to GW events, taking into account: (a) the relatively poor localization of these events in the early years of aLIGO, prior to AdVIRGO operations, and (b) the large uncertainty in the expected

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[1] http://toros.phys.utb.edu

[2] http://www.eso.org/public/teles-instr/e-elt/

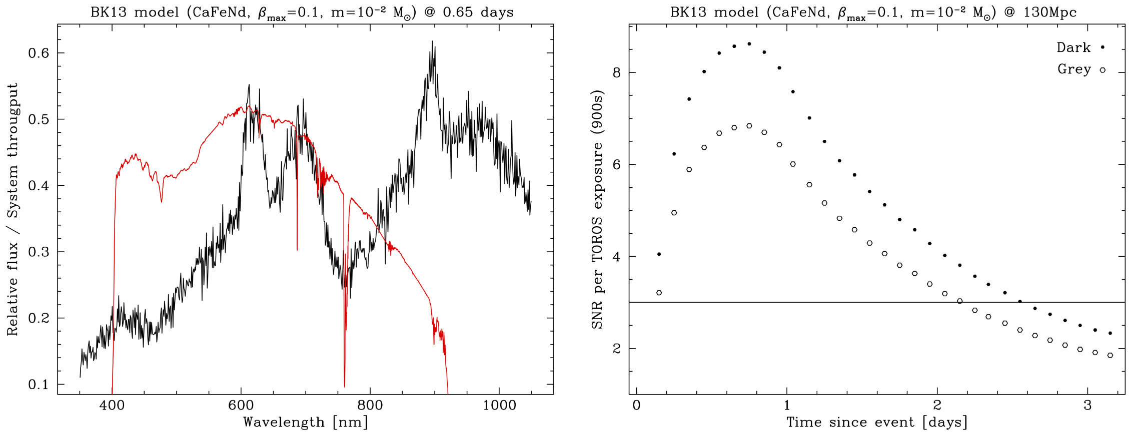

Figure 1: Left: Predicted spectrum at peak luminosity (in black) of the EM counterpart of a NS-NS merger, based on one of the latest models by Barnes & Kasen (priv. comm.); the expected total system throughput for TOROS is overplotted in red. The blue sensitivity will be helpful if the NS-NS merger produces a tidal tail of ^{56}Ni, as predicted by some models. Right: Expected SNR of an EM counterpart observed by TOROS as a function of time for the model on the left at the top-quartile distance predicted by the two-interferometer scenario of Kasliwal and Nissanke [12].

optical/near-infrared luminosity and duration of these events [11]. The left panel of Figure 1, based on one of the latest models by Barnes & Kasen (priv. comm.), shows the predicted spectrum of the EM counterpart of a NS-NS merger at peak luminosity and the system throughput for TOROS.

Our survey strategy is based on the two- and three-interferometer coincident-trigger scenario (aLIGO only, 2015-2016; aLIGO+AdVIRGO, 2016/17 and beyond) considered by Kasliwal and Nissanke [12], based on simulations by Nissanke, Kasliwal and Georgieva [13]. The most likely trigger rate for NS-NS mergers is ~ 50 yr^{-1}, with a median localization area of 250 sq.deg. and $\langle D \rangle = 180$ Mpc. The corresponding values for the top quartile of events are 170 sq.deg. and $\langle D \rangle = 130$ Mpc. The addition of a third interferometer increases the event rate to ~ 120 yr^{-1} and significantly reduces the median localization area to 17 sq.deg. The area of extragalactic sky accesible to TOROS on any given night ($d < 35^\circ, |b| > 15^\circ$, elevation$> 30^\circ$ for > 3 hrs) ranges between $7 - 11 \times 10^3$ sq.deg. depending on the time of the year. This implies an observable trigger rate of $0.7 - 1.1$ month^{-1} for the two-interferometer scenario and $1.8 - 2.7$ month^{-1} for the three-interferometer case.

We plan to obtain 15-minute exposures so that we can fully cover the median localization area of the two-interferometer scenario even in the shortest nights of the year, while obtaining a sufficient SNR for the EM counterpart of a GW event at the median distance ($I = 21.7$ mag, based on the model shown in Fig. 1). We expect $4 - 5\sigma$ detections at peak magnitude under grey/dark sky conditions, improving to

$7-9\sigma$ for the top quartile of events ($I = 21$ mag). Taking overheads into account, our system will be capable of covering the entire median localization area for the two-interferometer scenario (250 sq.deg. or 26 pointings) in 7 hours. Once AdVIRGO comes online (2016/17) we will be able to cover the median localization area in just two pointings, increasing our combined SNR at the end of night of imaging by $\sim 3.6\times$.

Except for the first four GW alerts from LVC, which will be governed by the aforementioned MoU, we will promptly release coordinates of potential transients and stacked images to the entire astronomical community. Additionally, we plan to execute our own photometric and spectroscopic followup.

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