# INAF – TIME ALLOCATION COMMITTEE

**Application for observing time** **Category: D**

**Period AOT39 (April 2019 – September 2019)** **Submit using: www.tng.iac.es/submit.html**

**1. Title**

REM contribution to the world-wide search for an electromagnetic counterpart of a gravitational wave trigger

**2. Abstract**

The gravitational wave (GW) era has started with the detection by A-LIGO of the in-spiral of two $\sim 30\ M_{\odot}$ black holes (GW150914). Almost two years later the LIGO and Virgo jointly detected the first GW signal from the merger of two neutron stars. Prompt optical follow up (including REM) discovered in the $33$ deg$^2$ error region a bright counterpart 10 arcsec off-center of the S0 galaxy NGC 4993, at a distance of 40 Mpc. The multi-messenger era started. Even with Virgo, error regions of GW triggers are large and a number of target galaxies is present. As for GW170817 a sieving process will start soon after the trigger searching for possible transient optical-NIR events. REM thanks to its fast slewing capabilities is well suited to target, on a short time scale, a large number of relatively bright ($r \sim 20$) host galaxies searching for new transients.

**3a. Number of requested hours per telescope and instrument**

| TNG | | | | | REM | |
|---|---|---|---|---|---|---|
| DOLORES | DOLOR.+MOS | NICS | HARPS-N | GIANO-B | ROSS | REMIR |
| | | | | | 20 | 20 |

**3b. Observing modes**

| | | | | | | |
|---|---|---|---|---|---|---|
| TNG: | | Visitor | | Service | | ToO |
| REM: | X | Rapid Response | | Queuing | X | ToO |

**4a. Preferred months**

first choice: second choice:

**4b. Other scheduling constraints** (use also box 14)

**5a. Past and future of the project**

a) Hours already awarded to the project:

b) Hours foreseen to complete the project:
(not including this request)

**6. Principal investigator**

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**7. Co-investigators (name and institution)**

P. D'Avanzo, S. Covino, A. Melandri, G. Ghirlanda, G. Ghisellini, O. Salafia, G. Tagliaferri (INAF-Brera), E. Palazzi, N. Masetti, L. Nicastro, A. Rossi, (INAF-OAS Bo), M. Branchesi (GISSI), G. Greco, G. Stratta (Univ. Urbino), E. Brocato, L. Stella, S. Piranomonte (INAF-OAR), V. D'Elia (ASI-ASDC), S. Benetti, E. Cappellaro, L. Tomasella (INAF-OAPD), A. Grado, F. Getman, L. Limatola, M.T. Botticella, M. Della Valle (INAF-OANa), on behalf of the GRAWITA collaboration.

## 8. Status of the project

| Telescope | Instrument | Date | Hours | Notes |
|---|---|---|---|---|

**Description**

20 hr were awarded during AO34, AO35, AO36, AO37, and AO38. During AO35 the observing time has been used to cover GW170817.
20 hr were awarded during AO38 and not yet used.

**Publications**

Publication obtained with direct REM data:

– E. Pian, P. D'Avanzo, et al. 2017, Nature 551 67: Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger
– P. D'Avanzo, G. Greco, et al., 2017, GCN 20693: LIGO/Virgo G274296: REM optical/NIR observations
– A. Melandri, P. D'Avanzo, et al. 2017, GCN 20776: LIGO/Virgo G275697: REM optical/NIR observations
– P. D'Avanzo, G. Greco, et al. 2017, GCN 21495: LIGO/Virgo G297595: REM optical/NIR observations
– A. Melandri, S. Campana, et al. 2017, GCN 21532: LIGO/Virgo G298048: REM optical/NIR observations of candidate in NGC 4993
– A. Melandri, P. D'Avanzo, et al. 2017, GCN 21556: LIGO/Virgo G298048: REM optical/NIR observations
– A. Melandri, P. D'Avanzo, et al. 2017, GCN 21596: LIGO/Virgo G298048: further REM optical/NIR observations of candidate in NGC 4993

**9a. If this proposal is a part of a PhD thesis, write here the name of the student, the thesis title and briefly describe the relevance of these observations for the thesis goals.**

**9b. Is this, or a similar application submitted to other time allocation committees (e.g. ESO, TNG-CAT, ITP)? If yes, please specify which and explain if and why the proposals should be considered complementary.**

This proposal is part of the INAF effort for the search of electromagnetic counterparts of GW triggers, following the MoU between INAF and the Ligo-Virgo Collaboration (LVC).

**10. Description of the programme (max. 3 pages, including references, tables, and figures.)**

*A) Scientific rationale* On 2015 Sep. 14, with the detection of the first gravitational wave (GW) signal by the two advanced LIGO (aLIGO) interferometers, the gravitational wave era started. During O1-O2 runs 6 events were detected. Virgo joined the two LIGOs during the last month of O2 (August 2017). The last one, GW170817, was associated for the first time to the binary merger of two neutron stars. While the detection of GWs was a scientific achievement of paramount importance, in order to connect it with a greater astrophysical context, it is essential to find electromagnetic (EM) counterparts to GW. Our team (GRAWITA) is heavily involved in GW electromagnetic follow-up since the beginning of O1.

An epochal breakthrough occurred with the event GW170817 associated to the NS-NS merger and to the weak short GRB 170817A detected by the Fermi and INTEGRAL satellites (LVC, 2017, PRL; Goldstein et al., 2017, ApJL; Savchenko et al., 2017, ApJL). The proximity of the event ($\sim 40$ Mpc) and the relative accuracy of the localisation ($\sim 28$ deg$^2$, thanks to the joint LIGO and Virgo operations) led to a rapid ($t < 11$ hr) identification of a relatively bright ($i \sim 17.3$ mag) optical counterpart, AT2017gfo (Coulter et al., 2017, Science). Detections of this source have been reported also in the UV (Evans et al, 2017, Science) and, at later times (days) in the X-rays (Troja et al., 2017, Nature) and radio (Hallinan et al., 2017, Science), suggesting for the possibility of off-axis GRB afterglow emission. Our team carried out targeted and wide field optical/NIR imaging observations of several bright galaxies within the reconstructed sky localisation of the GW signal with the Rapid Eye Mount (REM) telescope and with the ESO VLT Survey Telescope (ESO-VST). This led to the detection of AT2017gfo in the REM images of the field of NGC 4993 obtained just 12.8 hours after the GW/GRB event (Melandri et al. 2017, GCN 21532). Following the detection of this source, we started an imaging and spectroscopic follow-up campaign at optical and NIR wavelengths. Our unique dataset shows that the combined spectral properties and evolution of AT2017gfo are unlike those of any known supernova types. The analysis and modelling of the spectral characteristics of this source, together with their evolution with time, result instead in a good match with the expectations for kilonovae, providing the first compelling observational evidence for the existence of such elusive transient sources. The results of our photometric and spectroscopic monitoring of AT2017gfo are presented in Pian, D'Avanzo et al. (2017, Nature).

The single case of GW170817, besides representing an historical result, clearly demonstrates the vital importance of time-resolved optical/NIR imaging and spectroscopic follow-up of electromagnetic candidate counterparts of GW triggers. The scientific return will be enormous. GW/GRB170817 was the first discovered GW binary merger event involving NSs. An extraordinary result has been obtained first in the identification and then in the characterisation of the EM counterpart. We now have the long sought direct evidence that at least a fraction of SGRBs are indeed associated with compact star mergers and know that the basic predictions of the kilonova model are correct, but much has still to be done. Basic kilonova models are successful in explaining the major characteristics of the invaluable spectral sequence our team gathered with X-shooter (Pian, D'Avanzo et al. 2017), but fits are far from being acceptable. Lanthanides build up during the merger and single element opacities are barely known. Our spectral evolutionary sequence will provide a benchmark for any further model development. New events will clearly provide a stress test for these updated models in different conditions (Li et al. 2017, ApJ 844, 22), allowing us to disentangle micro-physics from viewing effects (geometry) and energetics (masses of the neutron stars, presence of a wind, hypermassive neutron star, amount of tidal debris, etc.). Finally, even if rarer (but detectable to a larger distance due to the larger mass involved), BH-NS merger events will further strain kilonova models. To this end, as demonstrated by the results we obtained so far, the REM telescope, combined with the facilities we have access to (see the Strategy section), will represent an invaluable asset.

*B) Scientific aim* Before GW170817 a strategy based on the full exploration of the large error box with large field of view instruments was foreseen. Transients discovered in this area will have then to be followed up and characterised. **One aim of the present proposal is to provide a spectral energy distribution (SED) of candidates counterparts of GW emitters coming from other large field of view observing facilities.** The most effective way to pinpoint the best candidates is through a colour selection and time evolution to allow spectroscopic facilities to focus on the best objects. In this respect the fast observing as well as the multi-filter observation capabilities of REM are perfectly suited to this aim. A single 10 min observation of $r < 20$ objects can provide on a fast track a SED ($griz$ and $J$), as well as a rough indication on the flux evolution, comparing REM data with the discovery image. In their follow-up campaign of GW150914, the PanSTARRS and PESSTO collaborations found $\sim 30$ transients with $r < 20$ (i.e. the REM limiting magnitude) in a sky area of $\sim 440$ deg$^2$, mainly type Ia SNe and AGNs (Smartt et al. 2016). This sets the number of expected targets for GW event.

GW170817 dramatically taught us that a targeted search is far more effective when the distance to the GW event is relatively small. This was indeed predicted since Gehrels et al. (2016) suggested that we can point to the brightest galaxies within the large error region to maximise the probability of finding the EM event. Within the GW170817 error region there were only $\sim 50$ galaxies (with $\sim 15$ being bright and massive) within the $90\%$ error region and estimated distance. This opened the possibility of a direct transient search, as occurred to GW170817. **We aim to observe all putative host galaxies within the error region of a GW event involving at least one neutron star, searching for new transients.** Based on the expected distance derived from the GW trigger we can tune the exposure in the 5-10 min range.

The next LVC run (O3) will likely take place in early 2019, thus overlapping with the present call. In addition, several engineer runs will take place in preparation of the start of O3. During these runs events can be detected as testified by the first GW event, GW150914.

**Figure 1.** REM caught the source of the gravitational wave GW170817 with its blue kilonova.

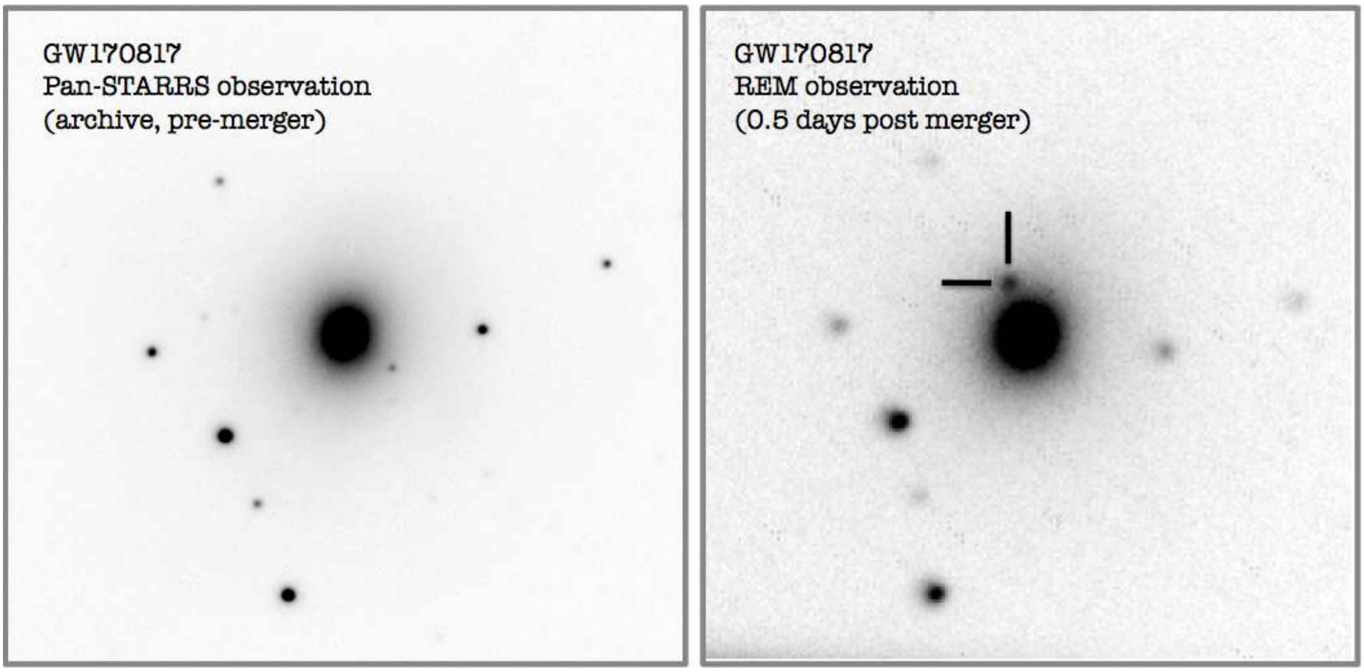
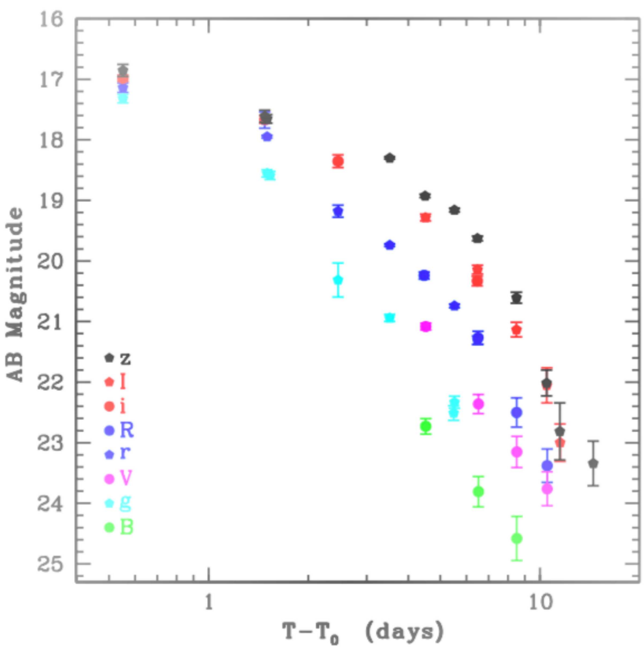



**Figure 2.** Multiband optical light curve of GW170817. The x axis indicates the difference in days between the time at which t observation was carried out T and the time of the GW event T0. The error bars are $1\,\sigma$. The data have not been corrected f Galactic reddening. REM data cover the first three sets, up to 2 d.



**11. List of targets** (note that the absence of a proper object list and information may weaken the proposal)

| Name | $\alpha$ | $\delta$ | Epoch | Mag. | Time | Additional Information |
|---|---|---|---|---|---|---|
| GW trigger | 00:00:00 | 00:00:00 | J2000 | $r < 20$ | 600s | Observe a number of candidate objects |

**12. Observational strategy and justification of requested time, including overheads.**

With the REM telescope we managed to obtain one of the earliest detection of the optical counterpart of GW 170817. This testifies that the discovery of the EM signal from a GW merger is feasible with REM.
After receiving a GW trigger we will point to the brightest galaxies within the error region. Gehrels et al. (2016) showed that if one considers the brightest galaxies that produce $\sim 50\%$ of the light, then the number of galaxies inside typical GW error boxes will be several tens. Combining the bright galaxy strategy with a convolution based on anticipated O2 GW localisations, about $23 \pm 4$ galaxies are expected and much less in O3, allowing to explore the $90\%$ error region. A quick monitoring (5-10 min depending on target distance) of the observable galaxies will spot any new bright transient.
In the meanwhile, if we will spot possible transients within the GW error region by other photometric survey (primarily VST and Campo Imperatore on our side, but also coming from other facilities), we will trigger our program on these objects. Each objects will be observed with a 600 s exposure. According to the REM ETC this will allow us to detect the source in any filter at a SNR of at least 3 (except $z$).
Interesting candidates will be followed up in the following nights.
The next scientific LVC run O3 is expected to begin in February 2019 with a duration of about one year (Abbott et al. 2016 Living Rev. Relativity, 19, Section 4). A full overlap with AO39 is envisaged. Despite this the importance of the electromagnetic detection of a GW event prompted us to apply for observing time. In addition, engineer runs will take place before the official start of O3, still leading to valuable candidate events. In light of the results obtained during the last 1 month of O2 (when both LIGO and Virgo were active) we expect up to several high significance GW trigger per month during O3 and possibly one per month involving a neutron star. The experience gathered during the past LVC runs indicates that the analysis of the images covering a GW sky localisation of tens of square degrees enables the detection of a relatively small number (5-10) of candidate counterparts on which detailed follow-up observations are then needed to unveil their nature. As GRAWITA collaboration we have access to a wide range of optical/NIR observing facilities such as the ESO-VST (2.6m, one deg2 field of view) and Campo Imperatore (0.9m, one deg2 field of view) for survey and the LBT (8m), Asiago (1.8m), the TNG (3.5m), and VLT (8m) telescopes for optical/NIR spectroscopic, as well as the 64m SRT radio telescope. Furthermore, many among our collaboration are members of the GW follow-up group of the Swift satellite, which is planned to promptly look for X-ray sources within GW skymaps. The use of such facilities, combined with the experience our team gathered during the past LVC runs, will ensure a careful search and selection of the candidate optical/NIR counterparts and an optimal use of REM to characterise and study them.

**13. Requested instrument(s) setup**

| Id | Instrument | Binning | Filter(s) | Slit | Grism | Time | Additional Information |
|---|---|---|---|---|---|---|---|
| 1 | ROS2 | $1 \times 1$ | g', r', i', z' | none | none | 20hr | |
| 2 | REMIR | $1 \times 1$ | z, J, H, K | none | none | 20hr | |

**14a. Moonlight constraints**

Max. # of days from new moon

**14b. Scheduling constraints, special requirements and other remarks**
(please include justification of constraints in 14a)

**15. Observational background of the applicants**

**Name of the observer(s) at TNG:**

**Experience of the observer(s) with the requested TNG instrument(s)**
Our team has been involved in the development of the REM telescope and its instruments since the very beginning of the project. Therefore we have all the required skills to drive and exploit these observations.

**Experience of the observer(s) with other telescopes/instruments**