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C. Reylé, J. Richard, L. Cambrésy, M. Deleuil, E. Pécontal, L. Tresse and I. Vauglin (eds)

SEARCHING FOR GAMMA-RAY COUNTERPART OF GRAVITATIONAL WAVE TRANSIENTS

H. Sol[1]

Abstract. With the recent direct detection of gravitational waves (GW), the search for electromagnetic counterpart of gravitational transients appears as a new challenge for astronomers. Information provided by electromagnetic data is complementary to the one deduced from the gravitational signal. Detecting the same event through the two messengers would be highly interesting to better identify the sources and refine their parameters. The scarcity of cosmic sources detected at very high energy (VHE) suggests that the gamma-ray domain could be useful to catch first electromagnetic signatures and reduce error boxes. Present IACT (Imaging Atmospheric Cherenkov Telescopes) like the High Energy Stereoscopic System (H.E.S.S.) operating in Namibia, the Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC) in the Canary Islands and the Very Energetic Radiation Imaging Telescope Array System (VERITAS) in the USA are already participating in the electromagnetic follow up of LIGO-Virgo gravitational wave event candidates. In the next decade the Cherenkov Telescope Array (CTA), operating with a larger field of view, a higher sensitivity in the VHE gamma-ray range between 20 GeV and 300 TeV, and a fast re-positionning, will be perfectly adapted to this observational program.

Keywords: very high energy astrophysics, gamma-ray astronomy, gravitational wave transients, electromagnetic counterparts

1 Introduction

Multimessenger gravitational wave astronomy aims to coordinate observations with a large variety of electromagnetic and non-photonic detectors to benefit from the synergy expected when combining different data of the same gravitational event. Joint observations can allow to better identify the source and determine independently its sky location and distance, to refine all parameters (even the ones deduced from the GW signal), and to confirm the GW detection and the nature of the event by providing complementary clues to implement a detailed modeling of the emitting source (Sathyaprakash, Schutz 2009). Information on the orientation of the source, on its cosmic environment, origin and evolution can also be deduced, with an interesting potential for discovering new types of sources and phenomena. There are various ways to achieve the goal of multimessenger GW astronomy. The most challenging one at the moment is to follow up GW transients by multimessenger instruments. This requires either all-sky surveys and monitoring, or a very efficient global alarm network to trigger quick observations of targets of opportunity, or else the possibility to predict the location and the time of GW events early enough to have the opportunity to plan multimessenger campaigns in advance. Another quite promizing approach is to look afterwards in recorded GW data for positive GW signal at the time of specific cosmic events like gamma-ray bursts (GRB) detected by electromagnetic instruments, which allows in addition to lower the GW detection threshold. Indeed refining the parameters used in the GW search, thanks to electromagnetic data obtained on the source, can change a GW event candidate into a confirmed GW detection. Given the benefit expected from such counterpart detection, the astronomical and astroparticle community has responded very positively to the call of the LIGO-Virgo collaboration in 2013. More than 70 Memorandum of Understanding have been signed, with more than 160 multiwavelength and multimessenger instruments ready to contribute to the search of GW transient counterparts, and among them several gamma-ray experiments particularly well suited for such stimulating project.

[1] LUTH, Observatoire de Paris, PSL Research University, CNRS, Place J. Janssen, 92 195, Meudon, France

2 Electromagnetic follow up of the first LIGO gravitational-wave events

GW150914, the first ever detected GW transient, was difficult to localize in sky position and in distance. The detection by only two GW instruments limited the accuracy and resulted in a large "error box" of about 600 squaredegrees (90% credible region). A distance of the order of 410 Mpc (z = 0.09) was estimated under some assumptions to solve the distance-inclinaison degeneracy. The "error volume" of about $10^7 Mpc^3$ then corresponds to about 10^5 galaxies! Moreover, this first GW transient happened to be due to the coalescence of two black holes, an event believed to possibly occur without any strong emission of electromagnetic waves (Abbott et al. 2016a,b). Despite all these difficulties, multiwavelength and multimessenger follow up of GW150914 was reported by at least 25 teams (see Fig. 1 and Fig. 2).

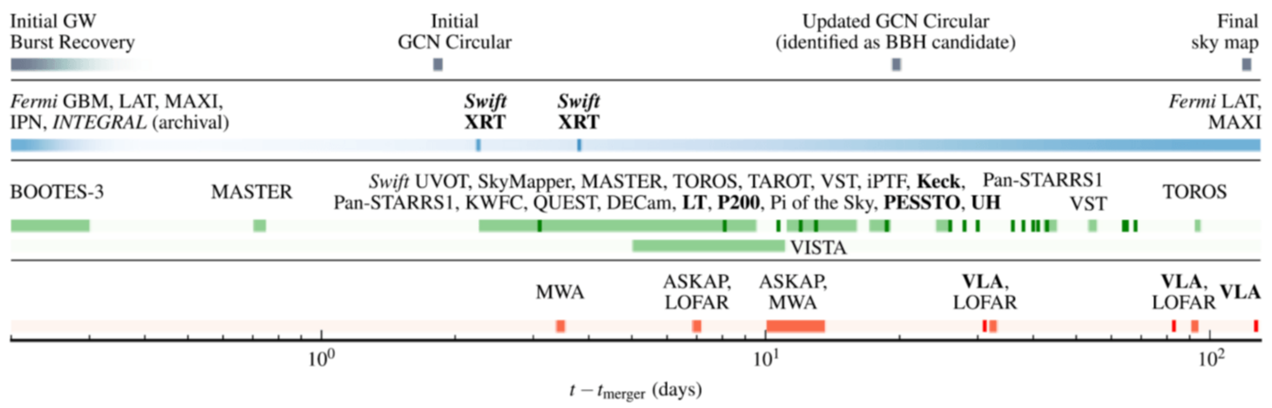

Fig. 1. Timeline of observations of GW150914 as a function of the observational delay following the GW trigger. From top to down: (I) GW observation and releases, (II) gamma-ray and x-ray, (III) optical and infrared, (IV) radio observations. From Abbott et al. (2016b).

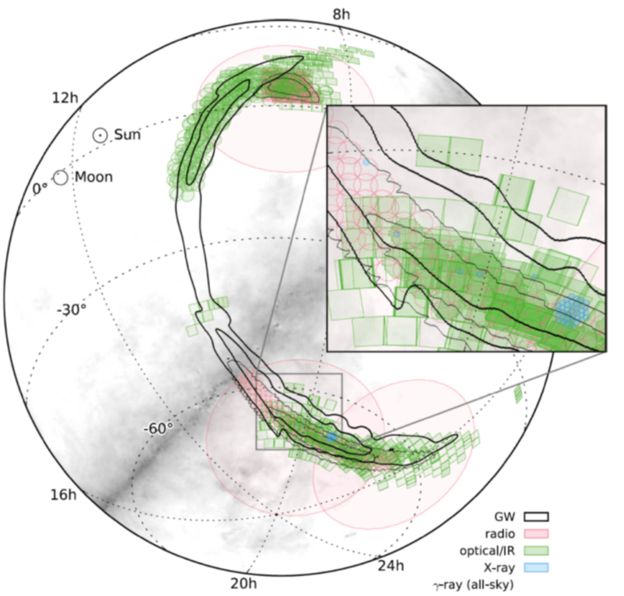

Fig. 2. Footprints on the sky of the observations listed in Fig. 1 (with same color code) overlaid on the 50% and 90% credible levels of different GW localization maps (black contours). All-sky surveys are not shown. Location of Sun, Moon and Galactic plane is given (Abbott et al. 2016b).

Work is still in progress but counterparts were extremely difficult to find. Many transients were detected in the region of interest but further investigation showed that they were not associated with the GW event. Only one possible counterpart was reported at the moment, namely a weak transient above 50 keV in the Fermi

Gamma-ray Burst Monitor data, recorded 0.4 seconds after the GW event and lasting 1 second, with a false alarm probability of 0.0022 (Connaughton et al. 2016). It is not yet clear whether this signal is a plausible counterpart or a chance coincidence. Indeed its characteristics suggest that it could be a weak GRB, consistent with the direction of GW150914. However it was not detected by other high energy instruments such as Fermi-LAT, INTEGRAL, AGILE, Swift or MAXI, which might be difficult to explain. Nevertheless further analysis of the Fermi-GBM data by Bagoly et al. (2016), with a new method to search for short-duration transients, finds a possible detection of counterpart of GW150914, and of LVT151012, a GW transient candidate reported by the LIGO-Virgo collaboration. If real, such association of short GRB with binary black holes mergers could be explained for instance by the scenario proposed by Perna et al. (2016) considering the evolution of a binary system with two low-metallicity massive stars, resulting in a "dead" accretion disk surrounding one of the black hole which can power the short GRB at the merger phase. More recent developments though did not find any candidate counterpart in the Fermi-LAT and GBM data (Racusin et al. 2016), neither for LVT151012, nor for GW151226, the second GW transient reported by the LIGO-Virgo collaboration (Abbott et al. 2016c). The search for electromagnetic counterparts remains completely open.

3 Ground-based gamma-ray astronomy and the Cherenkov Telescope Array project

During the last decade, the IACT experiments like H.E.S.S., MAGIC and VERITAS (see Fig. 3) showed the richness of our cosmos when seen in the TeV range, with the detection of various types of sources and especially compact ones with a number of pulsars and pulsar wind nebulae, supernova remnants, binary stellar systems, blazars, radio galaxies, and the galactic center. The sample of confirmed sources detected in the VHE range now include 178 objects. Present experiments are continuously gathering new results but their current sensitivity limits their possibilities of investigation.

CTA, the next generation main instrument of ground-based gamma-ray astronomy will benefit from improved performance, especially with an increase by a factor of ten of the sensitivity, a large spectral range, a large field of view of about 8 degrees, a better duty cycle and a fast re-positionning time down to 20 seconds (Acharya et al. 2013; Sol 2016a). CTA array will consist of several tens of Cherenkov telescopes of different types and sizes, with 23m, 12m and 4m telescopes in order to cover a wide domain in energy from 20 GeV up to 300 TeV (see Fig. 4). Two arrays are going to be implemented, one in La Palma, Canary Islands, and one in Chile near Paranal to have access to the whole sky. Lifetime should be 30 years.

Several prototypes of CTA telescopes and cameras have been implemented in the world especially in France, Germany, Italy, Poland, Switzerland and UK and are under construction in Spain and USA. Their first Cherenkov light has been obtained by the 4m prototype built and installed at the Observatoire de Paris in Meudon at the end of 2015 (Sol et al. 2016b). Production and deployment of the first telescopes on the two CTA sites are foreseen for 2017-2018.

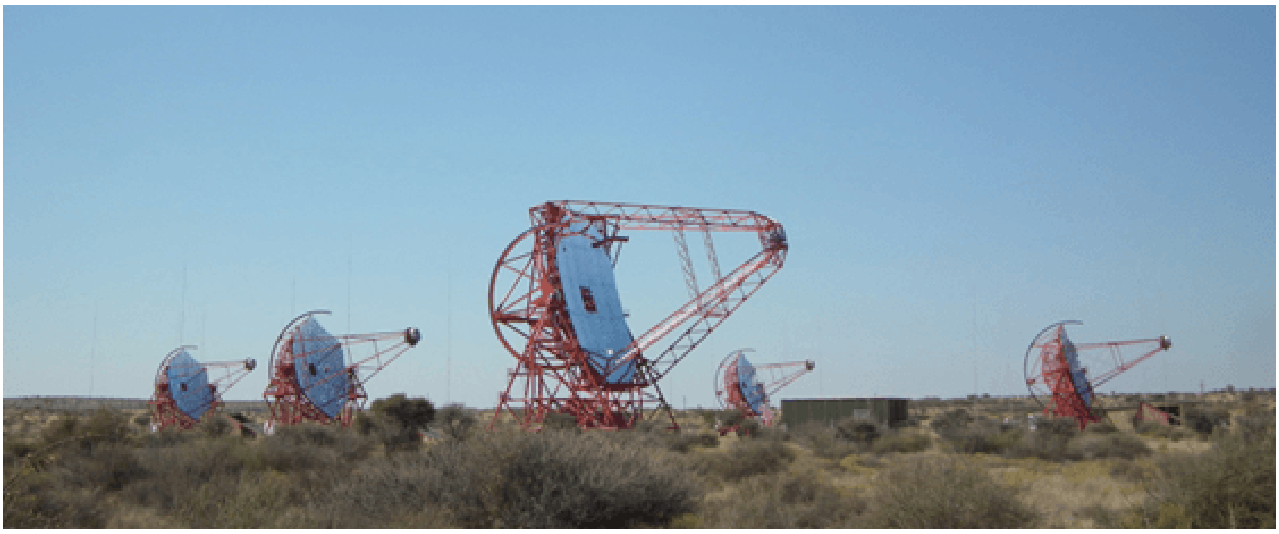

Fig. 3. The High Energy Stereoscopic System (H.E.S.S.) operating in Namibia.

Fig. 4. Artist's view of the future southern Cherenkov Telescope Array. Telescopes of different types and sizes allow to cover a very large domain in energy, from 20 GeV to 300 TeV.

At least a thousand of cosmic sources should be reachable with CTA. A special issue of Astroparticles Physics, volume 43, has been devoted to the CTA science case in 2013, with a large part dedicated to compact sources and various VHE phenomena potentially related to GW events. Especially some GRB should be detectable by CTA, with an expected detection rate of a few GRB per year (Meszaros 2013; Inoue et al. 2013). Indeed, thanks to its large detection area, CTA can resolve flares and variable emission on sub-minute time scales and appears as a very performant instrument to explore cosmic transients (see Fig. 5). The possibilities for searching GW transient counterparts are promizing. As shown by Bartos et al. (2014), CTA should be able to follow up GW event candidates over large sky areas. Despite several unknowns as regards to the electromagnetic properties of the relevant sources, it has the capability to detect some short GRB from compact binary merger events triggered by advanced LIGO-Virgo during its lifetime (see Fig. 6).

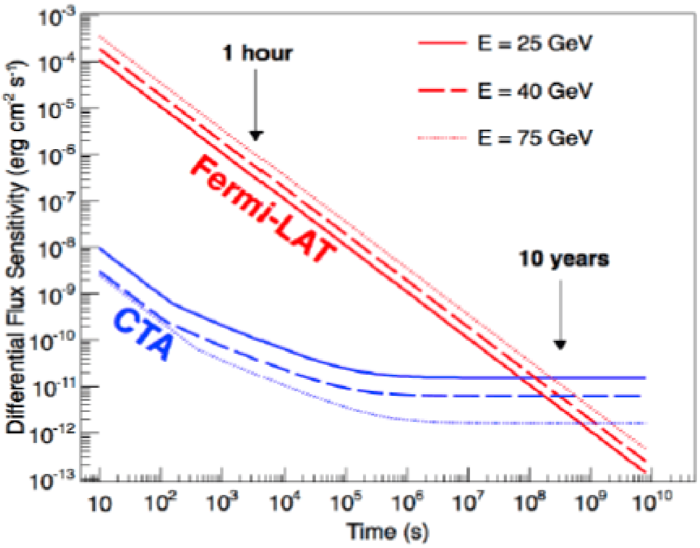

Fig. 5. Left: Differential flux sensitivity of Fermi-LAT and of CTA in the domain of overlap of their spectral range (namely from 20 GeV to 80 GeV) as a function of the time scale of interest. For time scales below 100 seconds CTA will improve the sensitivity by 4 orders of magnitude compared to the present Fermi-LAT performance (copyright@CTA).

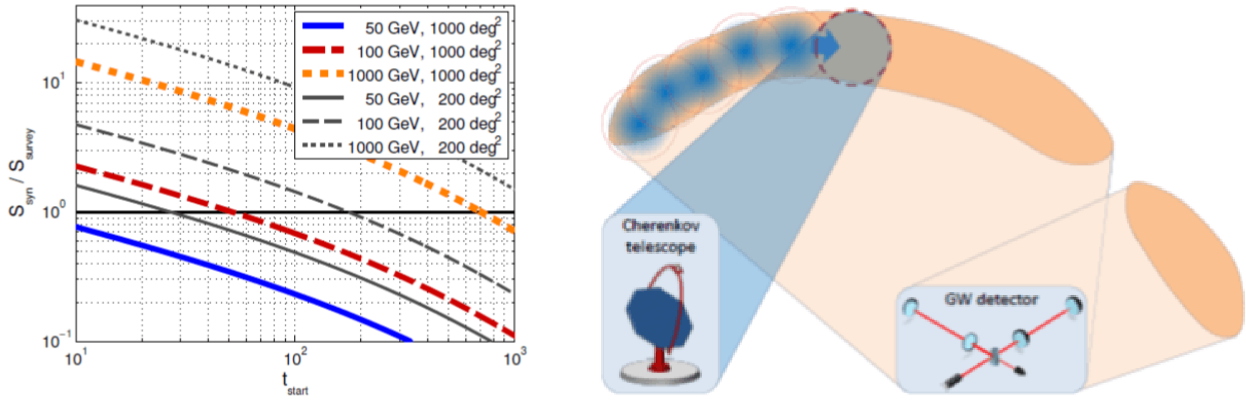

Fig. 6. Left: Detectability of a typical short gamma-ray burst with CTA as a function of the observationnal delay (in seconds) following the event. Results are shown for three different high-energy emission cutoff energies, and for two CTA survey operational modes. **Right:** Sketch of the sky areas of a GW event candidate and of the subsequent follow-up observation by a CTA telescope in survey mode. Actually several Cherenkov telescopes and GW detectors will be involved. From Bartos et al. (2014).

The nature of the GW event candidates and the detection rate per year of the different types of GW transients by LIGO-Virgo will be crucial to enable or disable the possible detection of counterparts. Current modeling of GRB offers many scenarios in which significant gamma-ray signal can be associated to GW transients. While the coalescence of isolated binary black holes could produce only faint or even no electromagnetic signal, gravitational collapses and mergers of binary systems with a neutron star or an accreting black hole are good candidates to be strong electromagnetic emitters at the time of the GW event, with the ejection of relativistic plasmas and jets and a wealth of possibilities to induce efficient and extreme particle acceleration by centrifugal forces, shocks, turbulence, or magnetic reconnection.

4 Conclusion and perspectives

Full operations of CTA are planned for 2022 and should last until 2050. CTA will open a window on the extreme, turbulent, transient and cataclysmic universe, mostly overlapping the realm of GW astronomy. The synergy between GW and VHE domains should be interesting. In this regard, strategies are being developped for global alarm networks between the large infrastructures of the coming decades in astrophysics and astroparticle physics (ALMA, AUGER, CTA, HAWC, Km3-IceCube, LHAASO, LIGO-Virgo, LOFAR, SKA and others), with the exchange of prompt alerts in a time delay limited to the record and analysis of the prime signal. The whole procedure raises many organizationnal questions that are currently under consideration.

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