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DOI

[10.1142/9789813270091_0002](https://doi.org/10.1142/9789813270091_0002)

Publication date

2019

Document Version

Final published version

Published in

Science with the Cherenkov Telescope Array

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Citation for published version (APA):

Markoff, S. B., Hinton, J. A., Ong, R. A., & Torres, D. F. (2019). Synergies. In The CTA Consortium (Ed.), *Science with the Cherenkov Telescope Array* (pp. 27-39). World Scientific. https://doi.org/10.1142/9789813270091_0002

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Synergies

CTA will have important synergies with many of the new generation of astronomical and astroparticle observatories. As the flagship VHE gamma-ray observatory for the coming decades, CTA plays a similar role in the VHE waveband as the SKA in radio, ALMA at millimetre, or E-ELT/TMT/GMT in the optical wavebands, providing excellent sensitivity and resolution compared to prior facilities. At the same time, the scientific output of CTA will be enhanced by the additional capabilities provided by these instruments (and vice-versa). MWL and MM studies using CTA provide added value to the science cases in two main ways:

Non-thermal emission: To understand the origin of cosmic rays and the extreme physical environments that produce them, it is necessary to study non-thermal signatures that span many orders of magnitude in frequency in the broad-band spectral energy distribution (SED) of a given object. In the case of time-variable emission, such studies require simultaneous observations and/or alerts and triggers between observatories.

Source properties: Information on the nature of gamma-ray emitting sources can be provided by MWL observations, enabling, for example, the object class, environmental conditions, or the distance to be established. For this purpose, simultaneous observations are in general not required, except for the need to characterise transient sources, for example in the case of gamma-ray burst redshift measurements.

The need for (simultaneous) MWL and MM observations has been considered as a factor in the site selection process for CTA and in the preparations for CTA science. Below, we describe the main areas in which synergies exist by

Figure 2.1: Timeline of major MWL/MM facilities over the next decade. Note that the lifetimes of many facilities are uncertain, contingent on performance and funding. We indicate this uncertainty via the gradient, but have chosen timelines based on the best information currently available. Instruments still in the proposal phase have been omitted, as have many relevant survey instruments mentioned in the text, for the sake of space.

waveband; see also a summary timeline of major facilities in Figure 2.1. We also discuss cases where agreements between CTA (Consortium or Observatory) are desirable, as well as cases where data can be obtained without agreement via publicly accessible archives. Detailed MWL/MM plans can be found in the individual KSP chapters. Please note that there are many important and complementary facilities to CTA the world over, and for the sake of space we cannot list them all, particularly the many existing survey instruments. We thus focus primarily on the newest developments, and this chapter is representative rather than exhaustive.

2.1 Radio to (Sub)Millimetre

Until a few decades ago, the radio band provided our main window to the non-thermal universe, via the cyclo-synchrotron emission of relativistic electrons that often dominates over thermal processes below ~ 10 GHz. Synchrotron emission goes hand in hand with particle acceleration, due to the inferred presence of magnetic fields and the presence of relativistic electrons, either directly accelerated or produced as secondaries. In addition, dark matter annihilation scenarios usually lead to the production of synchrotron-emitting secondaries along with gamma-ray emission.^a

The radio bands also have tremendous advantages for localising acceleration zones, because of the high angular resolution (e.g., down to tens of microarcseconds with VLBI) and the ability to observe in daylight. The combination of radio measurements with those at very high energies can provide limits on the electron density independent of assumptions about magnetic field strengths and can help determine which of several competing non-thermal processes dominate at the highest energies. Radio measurements also provide important magnetic field constraints via Faraday rotation and provide the ephemerides of known pulsars, to guide the search for potential gamma-ray pulsations with CTA. The success of Fermi-LAT in this regard relied on close cooperation with radio observatories [35]. An exciting recent development in the radio domain is the discovery of fast radio bursts [36, 37], with the possibility of high energy counterparts and potential synergies due to the wide field of view of CTA.

After decades of incremental improvements, radio astronomy has now again entered a rapid development phase. Many existing facilities have recently received major upgrades, providing much improved bandwidth and sensitivity (e.g., JVLA, e-MERLIN). At the same time, windows to entirely new parts of the radio spectrum at both low and high frequencies are finally being opened. In particular, the low-frequency bands (30–80, 120–240 MHz) are now being explored using LOFAR, which can monitor 2/3 of the sky nightly in Radio Sky Monitor mode and has a Transients Key Project dedicated to the detection, triggering, and cataloguing of new radio transients. In China, the Five-hundred-metre Aperture Spherical radio Telescope (FAST, 70 MHz to 3 GHz), the largest radio telescope ever built, had first light in 2016 and is now undergoing commissioning tests. A key new radio project is the Square Kilometre Array (SKA), whose phase 1

^aSee [34] for many examples.

will come online during CTA's science verification phase, followed by a ramp up to full operation with phase 2 by about 2024. SKA will have unprecedented sensitivity and excellent angular resolution, and the use of phased-array technology allows for a very large field of view, ideal for survey studies and transient detection (see Section 2.2). The pathfinders for SKA are very powerful instruments in their own right and will be important for early multi-frequency work involving CTA. A low-frequency pathfinder (MWA; 80–300 MHz) is well into its early science phase in Australia with upgrades in progress, and new projects at somewhat higher frequencies are under development in Australia (ASKAP; 700–1800 MHz and UTMOST; 843 MHz) and South Africa (MeerKAT; eventually 3 bands between 0.6 and 14.5 GHz). The ThunderKAT programme for transients with 3000 h of MeerKAT plus matching optical coverage (2017–2021) is particularly interesting for CTA. Finally, while not strictly a pathfinder for SKA, VLITE has just been commissioned with a wide bandwidth 330 MHz channel and large field of view (FoV) to conduct a new low-band survey of the sky, as well as detect new transients in real time. VLITE is a three-year pathfinder for the proposed LOBO project, a more extensive low-frequency radio monitoring project using the full JVL A. Having radio facilities in both hemispheres provides important complementarity for the two CTA sites.

CTA's sensitivity to diffuse emission around accelerators makes mapping of the interstellar gas over wide areas absolutely essential to enable identification of sources in the Galactic plane and within other large-scale surveys such as that of the LMC. (Sub)-millimetre wavelengths thus complement CTA science by offering a detailed understanding of the environment into which shock waves propagate and through which accelerated particles are transported and interact. Most relevant to CTA are the facilities geared to degree-scale surveys such as Mopra (Australia), APEX and Nanten2 (Chile), and Nobeyama 45 m (Japan), whose beam sizes are well-matched to CTA's arc-minute resolution. These telescopes measure molecular gas via a variety of molecular lines that trace the matter density over a wide range of scales. Of particular interest is the missing “dark” molecular gas now attracting serious attention in the ISM community, traced by THz lines, with pathfinder telescopes in Antarctica such as HEAT (USA/Australia) paving the way for large-scale survey instruments such as the proposed DATE5 project led by China.

The recently completed Atacama Large Millimetre/sub-millimetre Array (ALMA) represents a huge leap forward for (sub)-millimetre interferometry. With sub-arcsecond resolution and the sensitivity to probe a very wide

range of interstellar molecules, ALMA can carry out high fidelity probes of the density, temperature and ionisation level of material towards many CTA sources (including the LMC and nearby starburst galaxies), helping to understand the environments in which particles are accelerated and interact.

Furthermore, in recent years it has become clear that the sub-millimetre range is of particular interest for studying the particle acceleration processes in the jets of Galactic black hole transients (microquasars), as well as in the innermost regions of nearby AGN. For the former, there are many new small arrays and single-dish facilities in both hemispheres available. For the latter, the upcoming Event Horizon Telescope will link ALMA and other facilities in the first global VLBI array at millimetre/sub-millimetre frequencies, offering direct imaging of the jet-launching regions of key sources such as Sgr A* and M 87. Eventually mm/sub-mm observations together with CTA can be used to directly study the relation between near event horizon physics and cosmic-ray acceleration and non-thermal processes in astrophysical jets.

At higher frequencies, the microwave all-sky survey by the Planck mission (decommissioned in 2013) has produced a legacy archive that can be searched for very extended microwave counterparts to CTA sources within our Galaxy, complementary information on the lobes of nearby radio galaxies and nearby clusters, and constraints on Galactic magnetic fields.

2.2 Infrared/Optical through Ultraviolet and Transient Factories

Traditionally, the overlap between optical/infrared (OIR) astronomy and gamma-ray astronomy has been considered to be fairly small. Indeed much OIR emission has a thermal origin, such as stellar light, heated dust, or emission from HII regions. However, the last few years have revealed that many compact, high-energy sources emit detectable levels of synchrotron emission in the OIR, which can also display very fast variability. Some examples include blazars, microquasars, and pulsar-wind nebulae, all of which are high energy gamma-ray emitters, making OIR a new frontier also for MWL exploration, and especially for producing transient alerts. Some steady gamma-ray sources also display mixed OIR emission, such as the supernova remnant Cas A, which emits strong thermal emission but also has IR synchrotron-emitting regions. In addition, OIR studies of non-radiative shocks in supernova remnants can provide useful constraints on nonlinear particle acceleration and its influence on shock heating. Finally, OIR observations provide an interesting perspective in the case of gamma-ray

binaries, as properties of circumstellar discs may directly affect inter-wind shocks and lead to light-curve evolution.

There are too many existing smaller facilities to list here that will likely be useful for follow-up of CTA results, so we focus only on the larger developments. The high sensitivity of future telescopes will increase the number of sources for which one can identify non-thermal emission, or for which one can detect faint line emission from non-radiative shocks. By the time that CTA is operational, several very large, ground-based facilities will also come online. Already quite advanced is the project to build the European Extremely Large Telescope (E-ELT) in Chile, which will have diameter of 39 m and is expected to start operation by ~ 2024 . A similar project on the US side, the Thirty Meter Telescope (TMT) meant for Hawaii has run into some uncertainty with the site, but has enough momentum that it is likely to continue with a somewhat delayed timescale. The Giant Magellan Telescope (GMT) in Chile also begins commissioning in 2021, with diameter of 24.5 m. In space, the follow-up for the Hubble Space Telescope (HST) is the James Webb Space Telescope (JWST), launching in 2018. Similar to HST, the emphasis for JWST will be more on thermal sources, however HST has made some important progress for IR synchrotron-emitting sources and JWST's improved sensitivity will likely prove relevant for constraining several TeV-emitting sources. On the longer timescale, NASA has just placed highest priority on the O/NIR WFIRST mission, a wide-field survey instrument.

Optical polarimetry, as compared for example to radio, has not historically been of interest for MWL studies of VHE sources. It is becoming apparent, however, that polarisation offers an ideal way of isolating the synchrotron/non-thermal component in cases of mixed emission. This technique can be employed to provide new insights in broad-band SED correlations, for example to reveal potential low-energy signatures of otherwise orphan VHE flares. Additionally, polarisation studies of jets allow direct derivation of magnetic field parameters that can be used to improve SED modeling and emission-region localisation.

In general, the technical requirements for basic, but valuable, optical studies can be met at modest cost, suggesting that the installation of a small on-site (or nearby) optical telescope with polarimetric capability could significantly benefit the CTA science case. Having a dedicated facility for simultaneous, high cadence monitoring of AGN sources, as well as to follow-up transients or help trigger CTA programmes, could be an important addition to the Observatory capabilities. For example, several new VHE blazars were discovered from triggers based on high optical emission states

Figure 2.2: Results from the first season of RoboPol [38] blazar monitoring, simultaneously with Fermi observations in the GeV gamma-ray range. The fractional amplitude of a gamma-ray flare is plotted against the time delay between the gamma-ray flare and observed rotation in the optical polarisation angle. The length of the delay seems to be correlated with the gamma-ray flare amplitude. Red symbols show values prior to redshift correction. Reproduced from Ref. [39].

(see e.g. [40–42]), and optical polarisation shows interesting correlations with gamma-ray flares (see Figure 2.2). The addition of a dedicated optical telescope to the CTA baseline is under discussion within the project.

The newest development in the CTA context are the multiple initiatives for increasingly more sensitive, wide-field optical transient monitoring, collectively referred to as “Transient Factories”. Currently in operation are two ground-based facilities with $\sim 7\text{--}8\text{ deg}^2$ FoV, the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), and the “intermediate” Palomar Transient Factory (iPTF). The latter is itself a pathfinder for the Zwicky Transient Facility (ZTF) that will have a very large 50 deg^2 FoV, a survey speed of $3750\text{ deg}^2/\text{hr}$, and be online in 2017. On a similar timescale, the BlackGEM project, aimed to identify counterparts of gravitational wave (GW) sources, will focus on transient detection, particularly before GW sources are discovered, and will start operation in ~ 2018 with an initial deployment of three telescopes. All of these facilities use $< 1\text{ m}$ telescopes and in some sense pave the way for the Large Synoptic Survey Telescope (LSST), an 8 metre class telescope with a 9.6 deg^2 FoV that will scan the available sky every three nights with much higher sensitivity. By the time CTA is starting science verification, these facilities together with SKA and its

prototypes will generate overwhelming numbers of triggers (e.g., thousands each of GRBs and tidal disruption events, and likely hundreds of Galactic transients per year). Thus in the coming years, it is key to understand the potential for VHE follow-up and define appropriate response criteria, in order to select from the many transient alerts that will be supplied via subscribable streams such as VOEvent.^b Particularly, the earliest of these facilities will be proprietary in terms of sharing their transients alerts, exactly when the response modes of CTA need to be trained. To that end, agreements between CTA and some of these collaborations are likely to be beneficial and could also include triggering of the external facilities on CTA-detected transients.

Finally, the ultraviolet (UV) domain probes synchrotron emission of electrons which have comparable energies to those emitting inverse-Compton emission detected by CTA. As such, simultaneous UV observations of bright AGN, blazars and other variable objects can be extremely useful, as long as their emission is not too absorbed by interstellar gas. Swift, XMM-Newton, and ASTROSAT all have UV capabilities, and other missions are being proposed, but at the time of writing there are no definitive plans for a UV-capable space mission on the timescale of CTA.

2.3 X-ray

There is an obvious synergy between gamma-ray astronomy and X-ray astronomy. Phenomena which result in high enough temperatures for thermal X-rays to be produced are very often associated with shock waves, accretion, or high velocity outflows, and hence with particle acceleration and gamma-ray emission. In addition, studies of synchrotron and inverse-Compton emission in the X-ray domain have become increasingly important as missions capable of higher spatial resolution and sensitivity have been launched. In supernova remnants for example, the X-ray emitting electrons have ~ 100 TeV energies, making the combination of VHE gamma-ray and X-rays extremely powerful for constraining magnetic field strengths, the electron to proton ratio of the accelerated particles, and the particle energy distributions. The thermal X-ray emission from gamma-ray sources provides valuable information about plasma properties (e.g., temperatures, densities) and energetics (e.g., outflow/shock velocities). Non-thermal X-ray emission also provides a natural tracer of locations of extreme particle acceleration.

^b<http://wiki.ivoa.net/twiki/bin/view/IVOA/IvoaVOEvent>

Over the last decade X-ray astronomy has been very successful thanks to large missions such as Chandra and XMM-Newton, both spectro-imaging missions, plus several medium missions such as the Rossi X-ray Timing Explorer (RXTE, which pioneered many timing and monitoring studies), Suzaku (imaging-spectroscopy), and Swift (which continues to be extremely successful for transient detection and follow-up, including in the UV). NuSTAR, launched in 2012 and with a guest-observer programme started in 2015, is the first focusing telescope at hard X-rays and is currently making many exciting discoveries about extreme particle accelerators in the energy range 10–80 keV. MAXI, a Japanese all sky monitor, is currently in operation on the International Space Station, and the main X-ray transient detector besides Swift. More recently, CALET and the UFFO pathfinder have added additional hard X-ray/soft gamma-ray transient capabilities.

Chandra, XMM-Newton, and Swift will likely continue to operate throughout the early years of CTA operation, if not beyond. Several new missions have recently been launched or are funded, and will be very relevant for CTA science during its operation. For example, the German/Russian mission eROSITA (launch 2018; 0.3–10 keV imaging spectroscopy survey) will overlap with CTA's early operation years and further. eROSITA in particular will be the first imaging all-sky survey in the 2–10 keV range and, as such, it can be expected to provide a primary reference for CTA source identification and multi-wavelength correspondences. The data however will be proprietary, with the German side planning two data releases, one around 2021 and the other two years later at the end of the survey, ~2023. The Russian side will likely join in at least the final data release, but if CTA wants earlier access to survey data, as well as first pick of transients discovered in their offline (not real-time) pipeline analysis, a memorandum of understanding may be necessary. The loss of the Hitomi (earlier Astro-H) mission is clearly a major blow, but a replacement mission (XARM) has now been approved by JAXA.

Instruments with more focused capabilities include the recently launched (2015) Indian UV/X-ray satellite ASTROSAT, which features an all-sky monitor that will be very valuable for triggering CTA. An agreement may be necessary here as well. In June 2017, NICER was installed on the International Space Station (ISS) for soft X-ray timing focusing on primarily neutron stars and will be open for proposals in the second year. Also recently launched by China is the Hard X-ray Modulation Telescope (HXMT), a “super RXTE” operating in the 20–200 keV band with a 3600 deg² FoV.

Beyond that, the landscape for future X-ray missions is not yet fully determined but is looking very promising. SVOM is an optical/X-ray mission primarily for discovering GRBs, planned for launch in 2021. SVOM has similarities with Swift, triggering on bursts in both softer and harder bands, and following them in the X-ray and optical on-board. SVOM also includes a dedicated group of ground-based optical telescopes for wide FoV coverage before and after transient events.

Concepts under development which could provide synergies with CTA include the Chinese enhanced X-ray Timing and Polarimetry mission (eXTP), which incorporates large-area soft and hard X-ray telescopes, a wide-field monitor and a polarimeter, and would be launched around 2025. Several concepts related to Lobster-eye wide-field X-ray optics are being explored in the US, Europe, and in China. Such instruments could provide a major source of triggers for CTA transient observations.

The Athena+ project due for 2028 launch is, however, the next major observatory class mission, with good spatial resolution ($\sim 10''$), high sensitivity and energy resolution, and excellent spectroscopic capabilities. This mission will be the key X-ray facility for the 2030 decade and is designed for complementarity with radio/optical facilities and a large scientific breadth, providing additional high-energy constraints for CTA-detected sources.

One final development is the potential for X-ray polarimetry, a sure-fire way to isolate X-ray synchrotron from other components and to constrain the presence of accelerated particles. The IXPE mission has recently been selected by NASA as part of the SMEX programme. In the M4 ESA call, the X-ray Imaging Polarimetry Explorer (XIPE) was selected for a two-year design study as part of the Cosmic Vision programme. By the time of CTA's early science verification, the future for this exciting new capability should be clear.

2.4 Sub-VHE Gamma-ray Energies

The hard X-ray/soft gamma-ray domain (0.1–10 MeV) represents a very useful window on the non-thermal spectra of astrophysical sources, but is extremely challenging experimentally. Three main instruments currently contribute here: INTEGRAL, Swift-BAT, and Fermi-GBM. INTEGRAL was launched in 2002 and its lifetime has been extended through to 2018, and it may be extended further into the CTA early science period. The Fermi-GBM and Swift-BAT detectors are the critical current instruments for the detection of high-energy transients. Swift was launched in 2004 with

a nominal 10-year lifetime that has already been extended. In the 2016 NASA Senior Review, it reviewed first out of six missions, with operations confirmed through 2018 and recommended for extension at least until 2020. With an orbital lifetime stated as 2025 or beyond, it will likely continue to be a resource for transient detection during the CTA period.

At higher gamma-ray energies, the synergies with CTA are stronger and the instrumental performance is better matched to CTA. The GeV domain is dominated by pion decay, bremsstrahlung, and inverse-Compton emission, and in combination with the TeV range can help identify the dominant radiative mechanisms. CTA's lowest energy range overlaps with that of the two current instruments: the Fermi Large Area Telescope (Fermi-LAT) and AGILE. The Fermi mission has been so successful that its lifetime has been extended through 2018, and it will likely continue operating through 2020 and potentially beyond. NASA does not generally decommission fully operational missions, especially those with no clear successors, and Fermi's science performance continues to improve while having no consumables. The 2016 NASA Senior Review panel explicitly acknowledged the added scientific value of extending Fermi's lifetime so that it overlaps with CTA operations. Thus, it seems likely that Fermi will still be able to provide triggers and complementary coverage for a number of years of the CTA era. Fermi will continue to provide the main reservoir of extragalactic targets for CTA.

On the horizon, there are several missions upcoming or proposed to advance the observations of gamma rays from space in diverse domains. The Chinese Academy of Science's DAMPE (launched in 2015) and HERD (proposed for launch in the 2020's) are going to explore the energy range from hundreds of GeV to 10 TeV with an energy resolution approaching 1%. A few missions currently in the concept development phase (AMEGO in the U.S. and PANGU in China/Europe) aim at exploring the energy range from 0.5 MeV to 1 GeV with much improved sensitivity, point spread function, and polarisation capabilities thanks to the first-time ever combination of detection techniques based on pair production and Compton scattering in the same instrument. An alternative concept for a high-sensitivity, high-angular-resolution instrument with polarisation capabilities in the MeV to GeV domain uses gas time projection chambers. The concept is substantiated in two ongoing R&D projects, AdePT and HARPO. All of these future (potential) missions offer new and interesting synergies with CTA.

2.5 Complementary VHE Gamma-ray Instruments

Several ground-based VHE gamma-ray instruments may be operational at the same time as CTA. None of these instruments are direct competitors, but rather provide complementary performance. In particular, the High Altitude Water Cherenkov (HAWC) detector is a 100% duty cycle and very wide field of view (~ 1 sr) TeV range instrument [43]. Seated at a high-altitude site in Mexico, HAWC is capable of detecting the brightest known TeV sources in ~ 1 day and will be able to provide alerts to CTA for active/flaring states of blazars and transients. HAWC's modest ($\sim 0.5^\circ$) angular resolution and somewhat limited energy resolution gives it competitive sensitivity for very extended emission, and by the time of CTA, it will have mapped the northern sky to intermediate depth (see Chapter 6), identifying many interesting steady sources for CTA to investigate.

LHAASO [44], is an ambitious multi-component project incorporating HAWC-like water Cherenkov detectors and a very large array of scintillators at a site in China. LHAASO will complement CTA at higher energies in a similar way to HAWC, with modest resolution and background rejection power offset by high duty cycle, wide field of view, and large area. A number of concepts now also exist for a ground-particle-based detector for VHE gamma rays in the southern hemisphere, strongly complementing CTA-South by providing triggers and additional information on very extended emission regions.

One or more of the current generation of IACT arrays — H.E.S.S.-2, MAGIC and VERITAS — may continue operations into the CTA era. Use of these telescopes for monitoring could be considered, under suitable agreement between the telescope and CTA. In particular for cases when the CTA sites are at different longitudes than current IACTs, these can extend monitoring of bright flaring sources to periods before and after the CTA observations.

2.6 VHE and UHE Neutrinos

Essentially all mechanisms invoked for the production of high-energy neutrinos will also produce gamma rays of similar energies, and unlike charged cosmic rays, both point back to their sources. There is thus strong complementarity to observations with these two messengers. Gamma-ray telescopes, using e.g., the atmospheric Cherenkov technique, achieve the precision pointing and sensitivity to identify and understand populations of accelerators and to even localise acceleration sites in nearby objects.

Neutrino telescopes, using e.g., reconstructed muon tracks, are less able to precisely pinpoint the origin of neutrinos, but the neutrinos they detect are the only completely unambiguous tracers of hadronic acceleration, even out to high redshifts and beyond PeV energies, a combination that is not possible for gamma-ray telescopes due to photon–photon absorption.

The experimental situation in the VHE neutrino domain has recently dramatically altered, with the first strong evidence for astrophysical neutrinos above the MeV band. The IceCube collaboration has announced the detection of a diffuse astrophysical neutrino signal at 0.1–1 PeV energies [45]. Individual neutrino sources with a flux corresponding to $O(1)$ neutrino per IceCube exposure will be very easily detectable with CTA up to 1 PeV if they are Galactic in nature^c as has been suggested [46].

With the construction of KM3Net [47] and several upgrades to IceCube in the planning, the detection of individual neutrino sources is a distinct possibility. CTA is the ideal instrument to follow-up on any VHE neutrino clustering, necessary to localise and characterise the VHE accelerators. An important new aspect therein will be the follow-up of neutrino-generated triggers as ToOs, in order to localise and identify the hadronic accelerators.

2.7 Gravitational Waves

Now that gravitational waves from compact object merger events have unambiguously been detected by Advanced LIGO [7, 27, 28], a new and exciting field is opening up for electromagnetic follow-up and identification. Mergers of binary black holes and neutrons stars (or mixed systems) should be detectable out to a few hundred Mpc [48], with expectations of several to hundreds of GW transients per year after 2018 [49]. However, until the advent of third-generation detectors such as the Einstein Telescope [50], the localisation errors on these transients will be relatively large and asymmetric. For follow-up of GW alerts, CTA has huge advantages with respect to most other instruments and wavebands. These advantages include the large field of view and the flexibility to map very large and non-circular error boxes (which comes from the large telescope number [6] and potential divergent pointing modes), the rapid response time, and the less ambiguous nature of counterpart identification (when compared, for example, to the optical band).

^cUnless there is very strong internal gamma-gamma absorption, as might be the case for some binary systems.