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The Einstein Telescope

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The Einstein Telescope (ET) is a proposed European ground-based gravitational-wave observatory to explore the universe with gravitational waves up to cosmological distances. It is an evolution of the present second-generation detectors such as Advanced LIGO, Advanced Virgo, and KAGRA, leading to a sophisticated design including optimum site selection, and could be operating in the mid 2030s. There are several spectacular goals, shortly reported here, that can only be achieved through the detection of gravitational waves with a third-generation detector like ET, and other planned detectors like Cosmic Explorer in the U.S. For other goals, gravitational wave detectors are complementary to facilities exploiting electromagnetic radiation or other messengers, such as neutrinos and cosmic rays. Combined observations through GWs, electromagnetic signals, neutrinos and/or cosmic rays, will give us a multi-messenger and more comprehensive picture of many energetic phenomena of the Universe. The main scientific objectives and the potential for discoveries of ET in astrophysics, cosmology and fundamental physics are briefly reviewed.

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1. Overview

The first direct observation of gravitational waves (GW) emitted by a coalescing binary system made up of two black holes (BBH) in 2015 initiated the era of GW astronomy [1]. Two years later, the observation of the binary neutron star (BNS) merger GW170817 and its electro-magnetic counterpart was the starting point of the so–called era of multi–messenger astronomy [2, 3]. At present, after three observing runs, the number of detections amounts to almost hundred binary coalescence events, mainly BBH, but also 2 BNS and two neutron star–black holes (NSBH) [4].

Many remarkable results in astrophysics and in fundamental physics have already been obtained thanks to these first detections. To mention only a few highlights, the observation of the BNS coalescence GW170817 solved the long-standing problem of the origin of (at least some) short gamma ray bursts [2] [3]; the observations of the associated kilonova revealed that BNS mergers are a major formation site of the heaviest elements through r-process nucleosynthesis [5–8]; the observation of tens of BBH coalescences has revealed a previously unknown population of stellar-mass BHs, much heavier than those detected through the observation of X-ray binaries, and has shown that BBH exist, and coalesce within a Hubble time at a detectable rate. Concerning fundamental physics, cosmology and General Relativity (GR), the observation of the GWs and the gamma-ray burst from the BNS GW170817 proved that the speed of GWs is the same as the speed of light to about a part in 10^{15} [9]; the GW signal, together with the electromagnetic determination of the redshift of the source, provided the first measurement of the Hubble constant with GWs [10]; the tail of the waveform of the first observed event, GW150914, showed oscillations consistent with the prediction from General Relativity for the quasi-normal modes of the final BH [11]; several possible deviations from GR (graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.) could be tested and bounded.

The present second-generation detectors such as Advanced LIGO, Advanced Virgo, and KAGRA (LVK) have the potential to push their sensitivity further, but the possible enhancements are limited by the current available infrastructure. For this reason, since more than ten years, the GW community is preparing a third–generation of ground–based detectors: Einstein Telescope (ET) in Europe [12] and Cosmic Explorer (CE) in the US [13]. These instruments will be hosted in completely new facilities and feature major technological advancements as compared to the current second–generation detectors, resulting in a predicted gain in terms of sensitivity as large as one order of magnitude compared to LVK in a wide frequency range, as well as an extended bandwidth, especially towards frequencies below 10 Hz.

In its reference design, ET is planned to be a triangular–shaped configuration of detectors consisting of three nested interferometers of 60 degrees opening angle, with 10 km long arms. This will allow ET as a single–site observatory to disentangle both the polarisations of a GW signal, and to give the possibility to build a so–called null–stream, i.e. a combination of channels in which the GW signal cancels. Moreover, in this triangular case ET will feature a ‘xylophone’ configuration, with each of the three instruments consisting of two interferometers, one optimised for high frequencies, working at room temperature with 3 MW laser power circulating in the cavities and fused silica mirrors, and one optimised for low frequencies, thus with a lower power of 18 kW and working at cryogenic temperatures (down to 10–20 K) and silicon mirrors. The interferometers are planned to be built ~200 m underground to mitigate seismic and Newtonian noises, in an infrastructure capable to host future upgrades, thus giving ET the potential to lead the scientific landscape for decades. The scientific output that can be delivered by different detector configurations is currently under consideration, in particular a two L–shaped detectors built in well separated sites within Europe, instead of the single–site triangular–shaped detector described above. This matter is being studied in detail [14].

The ET project received a significant boost after the inclusion in the roadmap of the European Strategy Forum on Research Infrastructures (ESFRI) in 2021[15]. The year 2022 saw the formal birth of the ET Collaboration in Budapest, with more than 1400 researchers that already joined the Collaboration, and the European funding of the ET Preparatory Phase. Fundamental decisions regarding the design and the site(s) of the observatory are expected in the near future. The leap of about one order of magnitude in the sensitivity curve that can be achieved by ET and CE, as well as the extension to a few Hz in the accessible frequency range, result in extraordinary capabilities of these instruments.

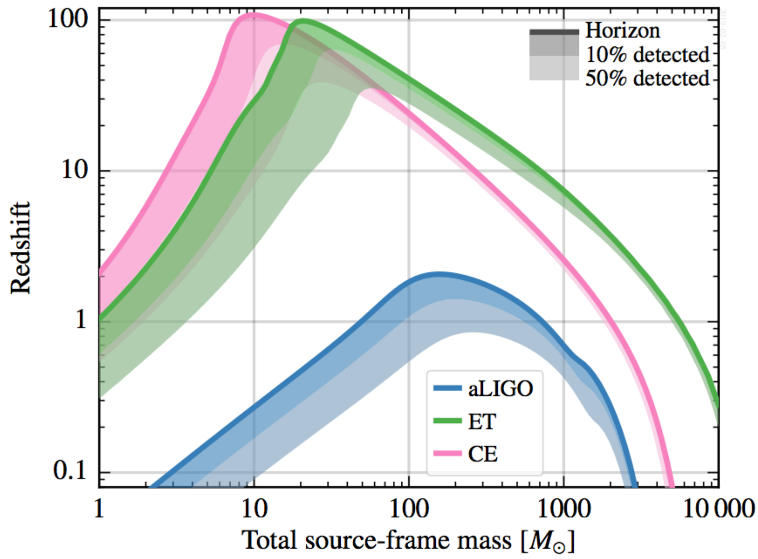

Figure 1: Astrophysical reach for equal-mass, nonspinning binaries for Advanced LIGO, Einstein Telescope and Cosmic Explorer (from ref. [16,17]).

An example of the extraordinary potential of third-generation detectors is provided by Fig.1, which shows the ET reach, in its reference design, in term of cosmological redshift, as a function of the total mass of a coalescing binary. While with Advanced LIGO and Advanced Virgo we could already detect high redshift sources, ET and CE could truly observe systems at cosmological distances, with BBHs being detectable out to z $\sim$ 100, where not even stars are expected to be present (thus objects found at these distances would have a primordial origin), and BNSs up to z $\sim 2 - 3$, beyond the peak of the star formation rate.
The larger frequency band will give the possibility to access new mass ranges for compact binary signals, extending both towards lower, sub–solar masses, to intermediate mass black holes, with masses above 10^3 M$\odot$. Also, thanks to its technological improvements, ET will have an outstanding performance in terms of the accuracy attainable on the reconstruction of the parameters of the observed sources.

2. ET science

ET has the potential to give extraordinary contributions to the domains of Astrophysics, Fundamental Physics and Cosmology opening a way towards new unexplored territories. We give here a brief overview of the main aspects of the ET science case. We refer the reader to [18-20, 14] for a detailed discussion.
Schematically, we can identify the following main items as part of the ET science case:

• Astrophysics
– Black hole properties: origin (stellar vs. primordial), evolution, demography.
– Neutron star properties: interior structure (QCD at ultra-high densities, exotic states of matter), demography.
– Multi-messenger astronomy: nucleosynthesis, physics of jets, role of neutrinos.
– Detection of new astrophysical sources of GWs: core collapse supernovae, isolated neutron stars, stochastic background of astrophysical origin.

• Fundamental physics and cosmology
– The nature of compact objects: near-horizon physics, tests of no-hair theorem, exotic compact objects.
– Dark matter: primordial BHs, axion clouds, dark matter accreting on compact objects.
– Dark energy and modifications of gravity on cosmological scales.
– Stochastic backgrounds of cosmological origin and connections with high-energy physics (inflation, phase transitions, cosmic strings, ...).

Many questions cross the borders between domains outlined above. For instance, understanding whether the BHs observed by GW detectors are of stellar or primordial origin obviously has an astrophysical interest, but a primordial origin would have deep consequences on our understanding of early Universe physics, inflation, etc., subjects that belong to the domain of cosmology and of fundamental physics. As another example, determining the equation of state in the core of neutron stars is of great importance both in astrophysics and for understanding the theory of strong interactions, QCD, in the regime of ultra-high density, where phase transitions can take place.
Summarising its potential, ET:
• is expected to detect most of the BBH merging in the Universe in the mass range probed by current observatories out to extremely high redshifts, with numbers of detections ranging from10^4 to 10^6 signals per year (depending on the still uncertain rate of these systems), i.e. thousands of detections per week. The number of detected sources and the level of accuracy expected in the reconstruction of their masses, spins and distances would allow us to perform a census of the BBH population across the Universe, potentially shading light on their (stellar) progenitors, formation channels, evolution and demography.
• could detect BBH mergers in completely new mass ranges as compared to LVK, extending towards sub–solar mass systems (whose origin can be primordial) and systems with objects of hundreds to thousands of solar masses, whose existence has yet to be probed, and that could constitute the seeds of supermassive BHs in the center of galaxies;
• could detect BNS and NSBH mergers well beyond the peak of the star formation rate with as

much as 10^5 to 10^6 signals per year. Like for BBHs, this would allow us to take a census of these systems in the Universe, potentially understanding their formation and evolution channels;
• could localise BNSs even as a single instrument, given the length of the signal in band (a GW170817–like source could last in the ET band more than one day) and identify the signal well before merger;
• could detect signals already identified by LISA, the Laser Interferometer Space Antenna, after 2034, which could observe the inspiral phase of some heavy BBH systems, that would then later merge in the ET band;
• could detect new astrophysical sources of GWs thanks to its improved sensitivity. These include the signal emitted by core–collapse supernovae (that would provide information on the mechanisms of these explosions as well as its post–collapse phase), continuous waves from isolated rotating NSs (that would give hints on the formation and evolution of isolated NSs, their structure, magnetic fields and spins) and potential burst signals from NSs;
• could observe 'golden events' with remarkably high SNR and an extremely accurate reconstruction of the source parameters, that would provide the possibility to perform stringent tests of GR both at the perturbative level, in the inspiral phase, where one could tightly test the validity of the post–Newtonian expansion, and in the merger and ringdown phases (which, for some events, could have an SNR $\gtrsim$ 100), where one can test the nature of the final compact object and the spacetime dynamics close to the horizon by observing its quasi–normal modes;
• could test various dark matter candidates, such as primordial black holes in binaries (in the same mass range as astrophysical BHs), ultralight bosons that could form clouds around BHs through 'superradiance', or dark matter particles accreting on compact objects, that could give signatures in the emitted signals;
• could allow us to study the nature of dark energy and possible modifications of GR at cosmological distances. Given the large redshifts accessible by ET, effects induced by non–trivial dark energy behaviours and by modifications of GR on cosmological scales become relevant and can be observed. At lower redshifts it is instead possible to measure the Hubble parameter value today, H_0, which is one of the key observables in cosmology. All these measurements provide independent information with respect to electromagnetic experiments.
• will search for astrophysical and cosmological stochastic backgrounds of GWs formed by the incoherent superposition of GWs emitted by different sources in the Universe. The cosmological stochastic backgrounds can be produced in the early Universe by several processes (phase transitions, inflation, cosmic strings) and could give us information about these processes. The astrophysical backgrounds is instead formed by the superposition of the GW signals emitted by astrophysical sources in the late Universe which cannot be resolved individually, and needs to be accurately characterised in order to access the cosmological one.

3. Conclusion

The Science Case of ET is broad, and addresses crucial problems in astrophysics, in cosmology and in fundamental physics, as summarized above. Furthermore, ET will be a discovery machine: GW detection has literally opened a new window on the Universe, and with third-generation detectors such as ET we will begin to look deeply through this window. This means that we will also penetrate into unexplored territories, and there, as the history of astronomy shows, surprises will likely await us.

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