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Abstract

The second-generation of gravitational-wave detectors are just starting operation, and have already yielding their first detections. Research is now concentrated on how to maximize the scientific potential of gravitational-wave astronomy. To support this effort, we present here design targets for a new generation of detectors, which will be capable of observing compact binary sources with high signal-to-noise ratio throughout the Universe.

Keywords: gravitational waves, cosmic explorer, LIGO

S Supplementary material for this article is available online

(Some figures may appear in colour only in the online journal)

1. Introduction

With the development of extremely sensitive ground-based gravitational wave detectors [1–3] and the recent detection of gravitational waves by LIGO [4, 5], extensive theoretical work is going into understanding potential gravitational-wave (GW) sources [6–15]. In order to guide this investigation, and to help direct instrument research and development, in this letter we present design targets for a new generation of detectors.

The work presented here builds on a previous study of how the fundamental noise sources in ground-based GW detectors scale with detector length [16, 17], and is complementary to the detailed sensitivity analysis of the Einstein Telescope (ET, a proposed next generation European detector) presented in [18, 19]. The ET analysis will not be reproduced in this work, but the ET-D sensitivity curve from [18] is used for comparison. It represents one 10 km long detector consisting of two interferometers [20], the detector arms forming a right angle. The ET design consists of three co-located detectors in a triangular geometry [21], but for the purpose of this letter we compare the sensitivity of single detectors, all with arms at right angles. (A comparison of triangular and right angled detector sensitivities can be found in [22].)

From this work two important conclusions emerge. The first of these is that the next generation of GW detectors will be capable of detecting compact binary sources with high signal to noise ratio (SNR > 20) even at high redshift ($z > 10$). The second is that there are multiple

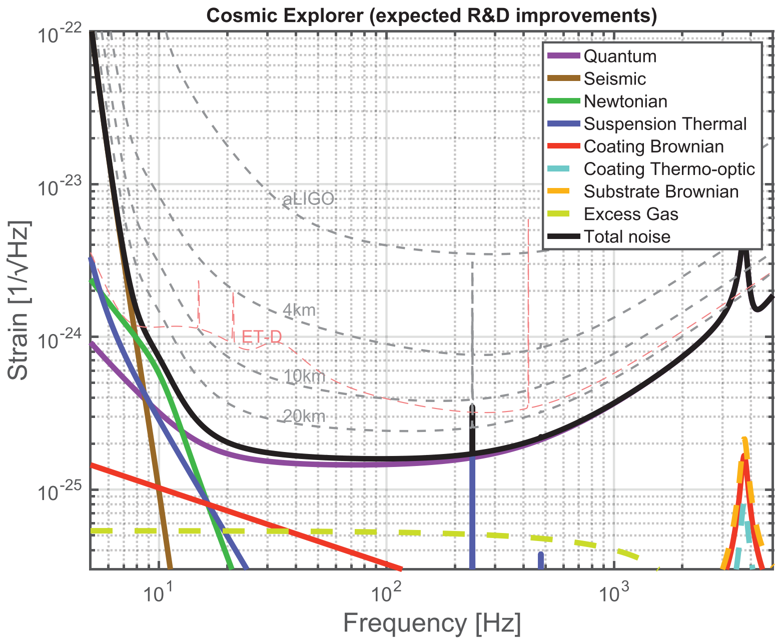

Figure 1. Target sensitivity for a next generation gravitational-wave detector, available from (stacks.iop.org/CQG/34/044001/mmedia), known as 'Cosmic Explorer' for its ability to receive signals from cosmological distances. The solid curves are for a 40 km long detector, while the dashed grey curves show the sensitivity of shorter, but technologically similar detectors; lengths are 4, 10 and 20 km. The Advanced LIGO and Einstein Telescope design sensitivities are also shown for reference.

distinct areas of on-going research and development (R&D) which will play important roles in determining the scientific output of future detectors.

In what follows, we start by expressing the sensitivity of a next-generation GW detector as a collection of target values for each of the fundamental noise sources. This is followed by discussions of the R&D efforts that could plausibly attain these goals in the course of the next 10 years. We conclude with a brief discussion of science targets, which will be accessible to a world-wide network of next-generation detectors.

2. Next generation sensitivity

The target sensitivity of a 40 km long next generation GW detector, known as 'Cosmic Explorer', is shown in figure 1 [23]. The in-band sensitivity and upper end of the band, from 10 Hz to a few kilohertz, is determined by quantum noise, while the lower limit to the sensitive band is determined by local gravitational disturbances (known as 'Newtonian noise' or NN [24]). Other significant in-band noise sources are mirror coating thermal noise and residual gas noise. Seismic noise and suspension thermal noise, though sub-dominant, also serve to define a lower bound to the detector's sensitive band. Each of these noise sources will be discussed in detail in the following sections.

The estimated sensitivities presented here are computed from analytical models of dominant noises and interferometer response in the sensitive frequency band of the detector. All of the contributing noise sources shown in figure 1 are intended as targets that could plausibly be attained by a number of on-going research programs, rather than curves linked to a particular technology. As such, in each of the following sections we give simple scaling relationships, which show how these noises scale relative to the relevant parameters, along with the values used to produce the target curves.

2.1. Quantum noise

Laser interferometer based GW detectors are almost inevitably limited in their sensitivity by the quantum nature of light. In most of the sensitive band, this limit comes in the form of counting statistics or 'shot noise' in the photo-detection process. Typically near the low-frequency end of the band a similar limit appears in the form of quantum radiation pressure noise (RPN), which can be thought of as the sum of impulsive forces applied to the interferometer mirrors as they reflect the photons incident upon them. A unified picture of quantum noise is, however, necessary to understand correlations between shot noise and radiation pressure noise and to appreciate the possibility of reducing quantum noise through the use of squeezed vacuum states of light [25–28].

In this letter, we use the now standard 'dual recycled Fabry–Perot Michelson' interferometer (DRFPMI) configuration, which is common to all kilometer-scale second generation detectors [1, 3, 29]. While this choice is considered likely for the next generation of detectors, a number of plausible alternative designs are being actively investigated [30–35].

For a DRFPMI, the optical response to GW strain is essentially determined by the choice of signal extraction cavity configuration[100]. We will assume for simplicity a 'broadband signal extraction' configuration, in which the signal extraction cavity is operated on resonance, and the detector bandwidth is set by the choice of signal extraction mirror reflectivity. Figure 2 shows the effect of increased signal extraction mirror reflectivity relative to that shown in figure 1; the detector bandwidth is somewhat wider, but the in-band sensitivity is reduced [26, 36, 37].

An important technology which will determine the quantum limited sensitivity of future GW detectors is squeezed light [27]. Squeezed states of light have been demonstrated to be effective in reducing quantum noise in GW interferometers [38, 39], and have been incorporated into the plans for all future detectors [16, 18]. The impact of squeezing on the scientific output of GW detectors has been studied in detail in [40]. In this analysis, we assume frequency dependent squeezing, as described in [41–43].

For any given DRFPMI configuration choice, the quantum noise is determined by the power in the interferometer, the laser wavelength, the level of squeezing at the readout, and at low-frequencies (where radiation pressure noise is dominant) by the mass of the interferometer mirrors. For any *fixed detector bandwidth*, the in-band sensitivity scales with respect to the target sensitivity as

$$\frac{h_{\text{shot}}}{h_{0\,\text{shot}}} = \sqrt{\frac{2\text{ MW}}{P_{\text{arm}}}}\sqrt{\frac{\lambda}{1.5\ \mu\text{m}}}\left(\frac{3}{r_{\text{sqz}}}\right)\sqrt{\frac{40\text{ km}}{L_{\text{arm}}}} \tag{1}$$

[100] The term 'signal recycling' is often used to refer to any interferometer configuration that uses a mirror at the output port of the interferometer to change the interferometer response. However, more careful language distinguishes between cases where this mirror *decreases* the signal storage time in the interferometer, known as 'signal extraction', and cases where it *increases* the signal storage time in the interferometer, known as 'signal recycling'.

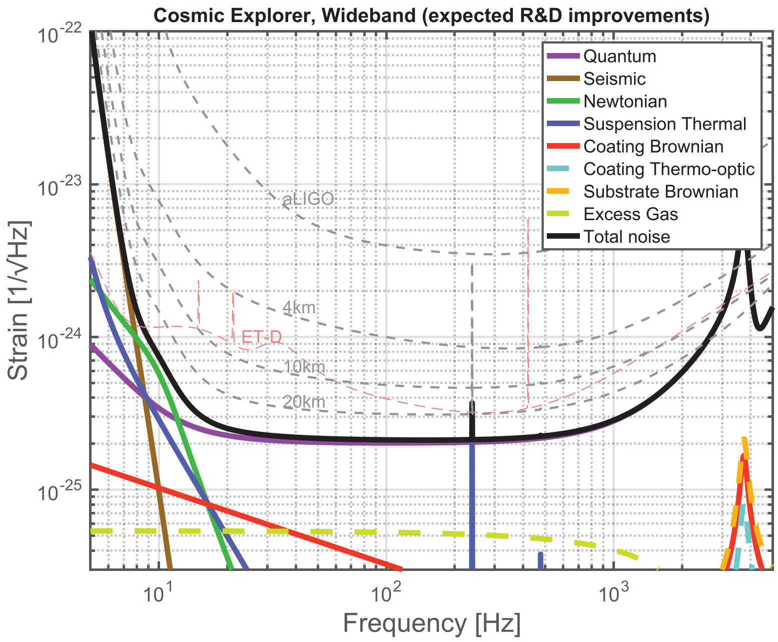

Figure 2. Similar to figure 1 but with a more reflective signal extraction mirror which gives a wider sensitive band, but is less sensitive in-band. The tradeoff between in-band sensitivity and bandwidth will need to be optimized to maximize specific science objectives (e.g. testing general relativity with black hole binaries, measuring neutron star equation of state, detection of GW from supernovae, etc). The dashed grey curves show the sensitivity of shorter, but technologically similar detectors; lengths are 4, 10 and 20 km.

$$\frac{h_{\rm RPN}}{h_{0\,\rm RPN}} = \sqrt{\frac{P_{\rm arm}}{2\ \rm MW}}\sqrt{\frac{1.5\ \mu\rm m}{\lambda}}\left(\frac{3}{r_{\rm sqz}}\right)\left(\frac{320\ \rm kg}{m_{\rm TM}}\right)\left(\frac{40\ \rm km}{L_{\rm arm}}\right)^{3/2},$$

where $P_{\rm arm}$ is the circulating power in the arm cavities of length $L_{\rm arm}$ bounded by mirrors of mass $m_{\rm TM}$, λ is the laser wavelength and $r_{\rm sqz}$ is observed squeezing level (e.g. $r_{\rm sqz} = 3$ corresponds to approximately a 10 dB noise reduction). The values normalizing each parameter in the above scaling relations are the ones used to produce the curves shown in figure 1, such that the resulting ratio (h_X/h_{0X}) is relative to the target noise amplitude spectral density. All of the values used to produce the target sensitivity curves are presented in table 1, approximate values for h_{0X} are given in table 2, and the exact quantum noise calculation is given in [36].

The exact choice of laser wavelength, for instance, is not important as long as longer wavelengths are accompanied by higher power. As an important example of this, consider two future interferometers; one uses fused silica optics and operates with 1.4 MW of 1064 nm light in the arms, while the other uses silicon optics and operates with 2.8 MW of 2 μm light in the arms. Both interferometers will have essentially the same quantum noise.

Interestingly, quantum noise does not scale inversely with length. This is due to the *fixed detector bandwidth* constraint, which requires increased signal extraction with greater length to maintain a constant integration time. While the shot noise appears to increase due to reduced

Table 1. Parameters used to produce the Cosmic Explorer (CE) target curve. The CE pessimistic and Einstein telescope, high- and low-frequency (HF and LF) parameters are included for comparison.

	CE	CE pess	ET-D (HF)	ET-D (LF)
L_{arm}	40 km	40 km	10 km	10 km
P_{arm}	2 MW	1.4 MW	3 MW	18kW
λ	1550 nm	1064 nm	1064 nm	1550 nm
r_{sqz}	3	3	3	3
m_{TM}	320 kg	320 kg	200 kg	200 kg
r_{beam}	14 cm	12 cm	9 cm	7 cm (LG_{33})
T	123 K	290 K	290 K	10 K
ϕ_{eff}	5×10^{-5}	1.2×10^{-4}	1.2×10^{-4}	1.3×10^{-4}

Table 2. Approximate values and frequency dependence for the Cosmic Explorer (CE) target curve using parameters in table 1. The frequency dependence for quantum noise given here is simplified and does not account for the details of frequency dependent squeezing [42]. All of these approximations fail when the frequency of the gravitational wave becomes comparable to the interferometer free-spectral-range (i.e. when $f \sim c/2L_{arm}$, or $f \simeq 3750$ Hz for $L_{arm} = 40$ km).

$h_{0\,shot}$	$\simeq$	$1.7 \times 10^{-25}\,\sqrt{1 + (f\,/\,400\text{ Hz})^2}$
$h_{0\,RPN}$	$\simeq$	$2.3 \times 10^{-25}\,(10\text{ Hz}\,/\,f)^2$
$h_{0\,CTN}$	$\simeq$	$6.0 \times 10^{-26}\,\sqrt{20\text{ Hz}\,/\,f}$
$h_{0\,gas}$	$\simeq$	5.4×10^{-26}

signal gain in the interferometer, the radiation pressure noise is reduced (both relative to $1/L$). A hidden dependence which is not included in equation (2) is the dependence of the mirror mass m_{TM} on length; longer interferometers generally have larger beams and thus require larger and more massive mirrors.

There are several areas of R&D which will determine the quantum noise in future detectors. The most immediate among these is work into increasing the measured squeezing levels [44–53]. Prototyping of the alternative configurations to demonstrate suppression of quantum radiation-pressure noise at low frequencies [54], and to investigate the influence of imperfections on this ability [55], is also on-going. Less easily explored in tabletop experiments, but equally relevant, are thermal compensation [56], alignment control [57, 58] and parametric instabilities [59–62], which determine the maximum power level that can be used in an interferometer. Finally, the ability to produce and suspend large mirrors will be necessary for any next generation GW detector [18, 63], and will have a beneficial impact on low-frequency quantum noise.

2.2. Coating thermal noise

Coating thermal noise (CTN) is a determining factor in GW interferometer designs; in current (second generation) GW detectors, CTN equals quantum noise in the most sensitive and most astrophysically interesting part of the detection band around 100 Hz [29, 64, 65].

Holding all else constant, CTN scales as

$$\frac{h_{CTN}}{h_{0\,CTN}} = \sqrt{\frac{T}{123\text{ K}}}\sqrt{\frac{\phi_{eff}}{5 \times 10^{-5}}}\left(\frac{14\text{ cm}}{r_{beam}}\right)\left(\frac{40\text{ km}}{L_{arm}}\right), \tag{2}$$

where T is the temperature, ϕ_{eff} is volume- and direction-averaged mechanical loss angle of the coating (defined below in equation (3)), and r_{beam} the beam size on the interferometer mirrors ($1/e^2$ intensity).

Thus, the brute-force techniques for reducing CTN are lowering the temperature and increasing the beam radius, while finding low-loss materials is an active and demanding area of research. For instance, the Advanced LIGO detectors were designed to minimize the impact of CTN by maximizing the laser spot sizes on the mirrors (at the expense of alignment stability in the interferometer), and the Kagra detector design is dominated by the incorporation of cryogenics to combat thermal noise [3, 66]. Similarly, current R&D into cryogenic technologies for future detectors is largely driven by the need to reduce CTN, either directly through low-temperature operation, or indirectly through changes in material properties as a function of temperature.

To be precise, ϕ_{eff} is the effective mechanical loss angle of the coating,

$$\phi_{\text{eff}} = \frac{\sum_j b_j d_j \phi_{Mj}}{2 \sum_j d_j} \tag{3}$$

in the notation of equation (1) in [65], where the summations run over all coating layers, d_j is the layer thickness, ϕ_{Mj} is the mechanical loss angle, and b_j is a factor of order unity which depends on the mechanical properties of the substrate and coating (numerically, $b_j \sim 2$ for most coatings). This is related to $h_{0\,\text{CTN}}$ by (again in the notation of [65])

$$h^2_{0\,\text{CTN}} = \frac{8 k_{\text{B}} T (1 - \sigma_s - 2\sigma_s^2)}{\pi r^2_{\text{beam}} L^2_{\text{arm}} \omega Y_s} \phi_{\text{eff}} \sum_j d_j, \tag{4}$$

where the summation gives the total coating thickness summed over all four test-mass mirrors (for the target design this is 16.6λ), Y_s is the Young's modulus of the mirror substrate, and σ_s is the Poisson ratio of the substrate.

It should be noted that a number of important dependencies are hidden in equation (2). In particular, ϕ_{eff} may have a strong dependence on T, and for a fixed cavity geometry r_{beam} grows with L_{arm} such that

$$\frac{h_{\text{CTN}}}{h_{0\,\text{CTN}}} = \sqrt{\frac{T}{123\ \text{K}}} \sqrt{\frac{\phi_{\text{eff}}(T)}{5 \times 10^{-5}}} \left(\frac{40\ \text{km}}{L_{\text{arm}}}\right)^{3/2} \tag{5}$$

is an equally valid scaling relation. Along the same lines, both r_{beam} and the coating thickness grow with λ, but they do so such that the effects cancel for fixed cavity geometry and finesse.

While the CTN curves in figures 1 and 2 are based on plausible extrapolations from current lab-scale results [67, 68], figure 3 shows a family of sensitivity curves which assume little or no progress is made in reducing CTN.

2.3. Newtonian noise

The motion of mass from seismic waves or atmospheric pressure and temperature changes produce local gravitational disturbances, which couple directly to the detector and cannot be distinguished from gravitation waves [24, 69, 70]. The power spectrum of such disturbances, known as 'Newtonian noise' (NN), is calculated to fall quickly with increasing frequency, such that while it presents a significant challenge below 10 Hz, it is negligible above 30 Hz. The level of NN present in a given detector is determined by the facility location (e.g. local geology, seismicity and weather) and construction (e.g. on the surface or underground), and defines the low-frequency end of the sensitive band for that facility.

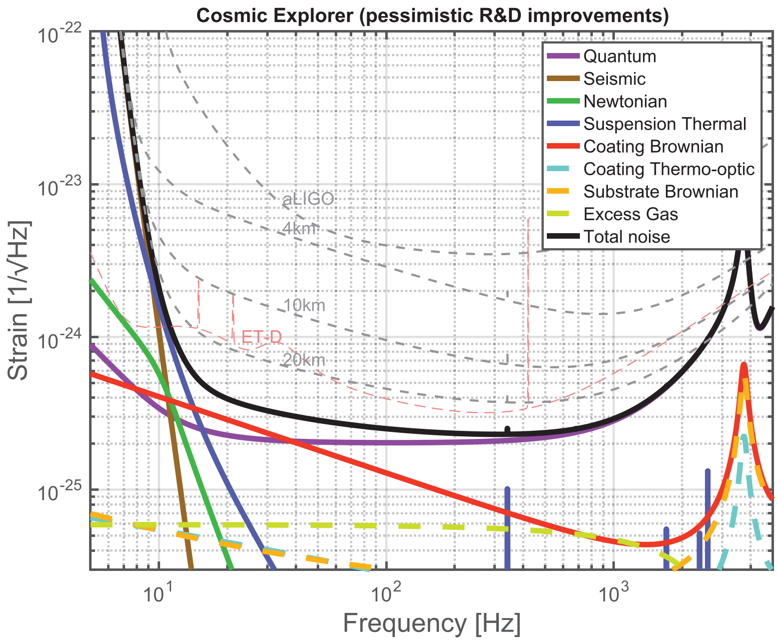

Figure 3. Similar to figure 2 but with coating and suspension thermal noise models which assume minimal progress. The wide-band signal extraction choice is made to minimize the impact of CTN. The proximity of the dashed grey 4 km curve to the Advanced LIGO reference curve reflects the fact that coating technology, which is nearly limiting in Advanced LIGO, becomes dominant over a range of frequencies given the reduction of quantum noise assumed for the future.

Active research in the area of NN will determine important aspects of the design of future GW detector facilities. Feed-forward cancellation of ground motion NN using a seismometer array has shown the potential to provide some immunity below 30 Hz [24, 71, 72], whereas concepts for feed-forward cancellation of atmospheric perturbations still need to be developed. It is also the case that the spectrum of atmospheric infra-sound and wind driven NN is, as yet, poorly understood and cancellation appears more challenging than for seismic NN [24]. Ongoing characterization of underground sites will also determine the gain for GW detectors with respect to NN reduction [73, 74], as future GW detectors may need to be constructed a few hundred meters underground if the sensitive band is to be extended below 10 Hz.

An important aspect of site characterization is to estimate the effectiveness of a NN cancellation system, which above all depends on the distribution of local sources, and for sub-10 Hz detectors also on the complexity of local topography [75].

Research in this area is developing quickly, and the NN estimates presented in this letter assume a factor of 10 cancellation of seismic NN

2.4. Suspension thermal noise and seismic noise

Suspension thermal noise and seismic noise, particularly in the direction parallel to local gravity (‘vertical’), can place an important limit on the low-frequency sensitivity of future GW detectors [76]. This is true both because, like NN, this noise source falls quickly with increasing frequency, but also because the coupling of vertical motion to the sensitive direction of the GW detector increases linearly with detector length (due to the curvature of the Earth), making the GW strain resulting from a fixed vertical displacement noise level insensitive to detector length [17].

Current research into test-mass suspensions is focused on supporting larger masses (required by detectors with $L_{\rm arm} > 10$ km), and longer suspensions for reduced thermal and seismic noise both in the horizontal and vertical directions [76]. Vertical thermal noise can be further reduced by lowering the vertical resonance frequency of the last stage of the suspension, possibly by introducing monolithic blade springs into the suspension designs [63]. The active seismic isolation concepts and systems developed for Advanced LIGO [77] will be adequate to support these new suspensions, though inertial sensors and tilt sensors with lower noise will be necessary if the suspension modes were reduced to lower frequencies.

2.5. Residual gas noise

Gravitational wave detectors operate in ultra-high vacuum to avoid phase noise due to acoustic and thermal noise that would make in-air operation impossible. The best vacuum levels in the long-baseline arms of current detectors are near 4×10^{-7} Pa $\simeq 3 \times 10^{-9}$ torr and are dominated by out-gassing of H_2 from the beam-tube steel. This noise scales with average laser-beam cross-section and arm length as [78]

$$\frac{h_{\rm gas}}{h_{0\,\rm gas}} = \sqrt{\frac{p_{\rm gas}}{4 \times 10^{-7}\ \rm Pa}}\ \sqrt{\frac{14\ \rm cm}{r_{\rm beam}}}\ \sqrt{\frac{40\ \rm km}{L_{\rm arm}}}\,. \tag{6}$$

3. Compact binaries at high red-shift and extragalactic supernovae

The high sensitivity of future ground-based gravitational wave detectors will considerably expand their scientific output relative to existing facilities. Clearly, sources routinely detected already by current instruments in the local universe will be detected frequently with high SNR, and at cosmological distances. Straightforward examples are binary systems involving black holes and neutron stars. These systems, referred to collectively as 'compact binaries' (CBCs), are ideal GW emitters and a rich source of information about extreme physics and astrophysics, which is inaccessible by other means [6–10, 14, 79].

Binary neutron stars (BNS) could yield precious information about the equation of state (EOS) of neutron stars, which can complement or improve what can be obtained with electromagnetic radiation [80, 81]. However, second-generation detectors would need hundreds of BNS detections to distinguish between competing EOS [82–84]. New detectors would help both by providing high SNR events, and increasing the numbers of threshold events [85].

In general, all studies that rely on detecting a large numbers of events will benefit from future detectors. Examples include estimating the mass and spin distribution of neutron stars and black holes in binaries, as well as their formation channels [86–88].

Furthermore, a GW detector with the sensitivity shown in figure 1 could detect a significant fraction of binary neutron star systems even at $z = 6$, during the epoch of reionization, beyond which few such systems are expected to exist [89]. Those high-redshift systems could be used to verify if BNS are the main producer of metals in the Universe [90], and as standard candles for cosmography [11].

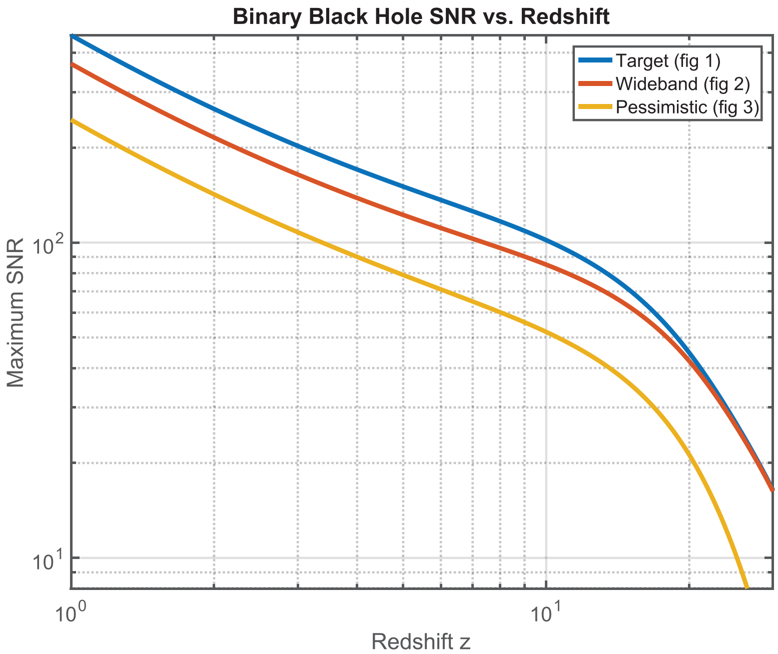

Figure 4. The maximum signal-to-noise ratio (SNR) for which GW detectors with the sensitivities shown in figures 1–3 would detect a system made of two black holes (each with an intrinsic mass 30 $M_\odot$), as a function of redshift. Many systems of this sort will be detected at $z < 2$ with an SNR > 100, enabling precision tests of gravity under the most extreme conditions.

Future instruments could detect a system made of two 30 $M_\odot$ black holes, similar to the first system detected by LIGO [4], with a signal-to-noise ratio of 100 at $z = 10$, thus capturing essentially all such mergers in the observable universe (see figure 4).

Nearby events would have even higher SNRs, allowing for exquisite tests of general relativity [91], and measurements of black-hole mass and spins with unprecedented precision. The possibility of observing black holes as far as they exist could give us a chance to observe the remnants of the first stars, and to explore dark ages of the Universe, from which galaxies and large-scale structure emerged.

Furthermore, future detectors may be able to observe GW from core-collapse supernovae, whose gravitational-wave signature is still uncertain [92, 93]. GWs provide the only way to probe the interior of supernovae, and could yield precious information on the explosion mechanism. Significant uncertainty exists on the efficiency of conversion of mass in gravitational-wave energy, but even in the most optimistic scenario the sensitivity of existing GW detectors to core-collapse supernovae is of a few megaparsec [94]. A factor of ten more sensitive instruments could dramatically change the chance of positive detections. In fact, while the rate of core-collapse supernovae is expected to be of the order of one per century in the Milky Way and the Magellanic clouds, it increases to ∼2 per year within 20 Mpc [95, 96].

4. Conclusions

We present an outlook for future gravitational wave detectors and how their sensitivity depends on the success of current research and development efforts. While the sensitivity curves and contributing noise levels presented here are somewhat speculative, in that they are based on technology which is expected to be operational 10 to 15 years from now, they represent plausible targets for the next generation of ground-based gravitational wave detectors. By giving us a window into some of the most extreme events in the Universe, these detectors will continue to revolutionize our understanding of both fundamental physics and astrophysics.

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