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Prospects for detecting gravitational waves at 5 Hz with ground-based detectors

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We propose an upgrade to Advanced LIGO (aLIGO), named LIGO-LF, that focuses on improving the sensitivity in the 5-30 Hz low-frequency band, and we explore the upgrade's astrophysical applications. We present a comprehensive study of the detector's technical noises, and show that with technologies currently under development, such as interferometrically-sensed seismometers and balanced-homodyne readout, LIGO-LF can reach the fundamental limits set by quantum and thermal noises down to 5 Hz. These technologies are also directly applicable to the future generation of detectors. We go on to consider this upgrade's implications for the astrophysical output of an aLIGO-like detector. A single LIGO-LF can detect mergers of stellar-mass black holes (BHs) out to a redshift of $z \simeq 6$, and would be sensitive to intermediate-mass black holes (IMBHs) up to $2000\,M_\odot$. The detection rate of merging BHs will increase by a factor of 18 compared to aLIGO. Additionally, for a given source the chirp mass and total mass can be constrained 2 times better than aLIGO, and the effective spin 3-5 times better than aLIGO. Furthermore, LIGO-LF enables localization of coalescing binary neutron stars (NSs) with an uncertainty solid angle 10 times smaller than that of aLIGO at 30 Hz, and 4 times smaller when the entire signal is used. LIGO-LF also significantly enhances the probability of detecting other astrophysical phenomena including the tidal excitation of neutron star r-modes and the gravitational memory effects.

Introduction.– The detection of gravitational waves (GWs) from coalescing binary BHs [1–5] by aLIGO [6] and Advanced Virgo (aVirgo) [7] heralded the era of GW astrophysics. However, detecting binaries that are more massive and further away than the current BH catalog is challenging. Since the merger frequency decreases as the total mass of the binary increases, systems more massive than a few $\times 100\,M_\odot$ will no longer lie in the most sensitive band of aLIGO. IMBHs are an example of systems likely to be missed by aLIGO [8–13] . At the same time, a pair of $30\,M_\odot$ BHs at $z = 2$ will appear to have a total mass of $180\,M_\odot$ due to the cosmological redshift [14], illustrating the difficulties of detecting even the stellar-mass BHs at cosmological distances. Therefore, improving the low-frequency sensitivity plays a crucial role in extending both the mass and spatial range of detectability.

Another scientific goal of GW detectors is to enable multi-messenger astronomy, as demonstrated by the detection of a merging NS binary in GW and the follow-ups by electromagnetic telescopes [15, 16]. To help the subsequent observations, GW observatories need to provide the source location not only accurately but also quickly. Since the time to merger scales with frequency f as $f^{-8/3}$, if the error area can shrink small enough at a lower frequency, the location information can be sent out at a much earlier time. Consequently, improving the low-frequency sensitivity allows for more timely follow-up observations.

In this Letter we propose an upgrade to aLIGO (and its evolution, A+ [17]) that enables a significant enhancement in sensitivity in the 5-30 Hz band, while maintaining

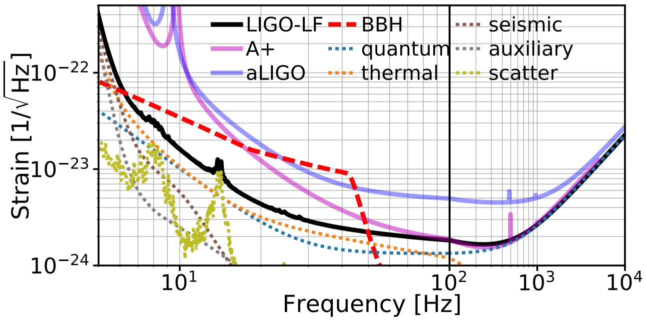

FIG. 1. Proposed sensitivity for LIGO-LF (solid-black) and its noise budget (dashed lines). Also shown in the dotted-red curve is the spectrum of a $200\,M_\odot - 200\,M_\odot$ binary BH merger (in the detector frame) at 10 Gpc. The LIGO-LF's sensitivity to such systems is greatly enhanced relative to aLIGO (solid-blue) and A+ (solid-magenta). Throughout the Letter, we will adopt the same coloring convention when we compare different sensitivities (i.e., we use black, magenta, and blue for LIGO-LF, A+, and aLIGO, respectively).

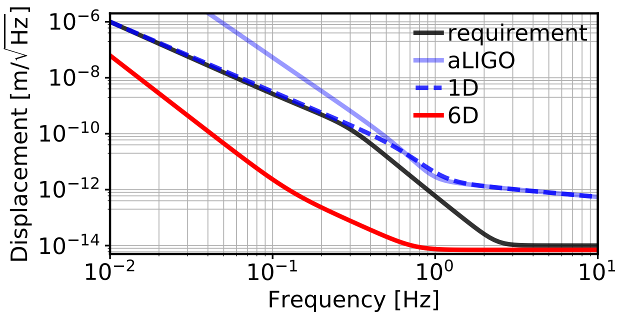

FIG. 2. Inertial sensor noise for aLIGO (blue) and the requirement for LIGO-LF (black). Custom tiltmeters can be used to improve aLIGO sensor noise below 0.5 Hz (blue-dashed). A novel 6D seismometer (red) can surpass the requirement in the entire band.

high frequency performance. This new design, dubbed "LIGO-LF", can be implemented on a timescale of ∼10 years and serve as pathfinder for later upgrades like the Voyager [18] and next generation detectors like the Einstein Telescope [19, 20] and Cosmic Explorer [21].

LIGO-LF design. – The current aLIGO sensitivity below 30 Hz is limited by non-stationary technical noises [22–24]. Here we describe the solutions we propose to reach the LIGO-LF sensitivity shown in Fig. 1.

The first element of the upgrade reduces the angular control noise. Angular motion of the optics is actively stabilized using wave-front sensors with a typical sensitivity of $5 \times 10^{-15}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ [23, 25]. The bandwidths of the arm cavity angular loops are set to 3 Hz to reduce the seismically induced motion to a few nrad rms. However, the control noise disturbs the test masses above 5 Hz and contaminates the GW readout via beam miscentering on the mirrors. We propose to further suppress the motion of the optical benches so that the control bandwidth can be lowered.

Despite the sophistication of LIGO's seismic isolation [26–28], it does not significantly reduce the microseismic motion at ∼ 0.2 Hz. This is due to tilt-to-horizontal coupling [29–31], which causes the noise of the aLIGO inertial sensors to grow as $1/f^4$ at low frequencies as shown in Fig. 2. To reduce the bandwidth of the angular controls to 1 Hz, the tilt motion needs to be suppressed to $10^{-10}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ in the 0.01-0.5 Hz band. The corresponding horizontal sensitivity is shown in Fig. 2. Above 1 Hz we require an improved sensitivity to reduce the direct coupling of the ground motion (see the Supplemental Material for a breakdown of the noise, which includes Ref [32]).

There are two approaches to reach the required sensitivity of the inertial seismic sensors. The first one is to actively stabilize tilt motion using custom built tiltmeters [33, 34], which can achieve the requirement below 0.5 Hz. The second approach uses a novel 6D seismometer [35]. In the core of this instrument is a quasi-monolithically suspended [36] mass whose position is monitored using interferometric readout. Fig. 2 shows that the design performance of the 6D seismometer satisfies the requirement in the entire band.

The radiation-pressure induced angular instability also limits the minimum bandwidth [37, 38]. We propose to increase LIGO-LF's test masses from 40 kg to 200 kg to mitigate the effects of radiation pressure. More massive test masses are also a fundamental part of next generation GW detectors.

The coupling of the longitudinal motion of the signal recycling cavity contaminates aLIGO's sensitivity in the 10-50 Hz band [23]. This coupling is proportional to the arm detuning [39] introduced to enable DC readout of the GW signal [40]. For LIGO-LF, we assume balanced-homodyne readout [41] will be implemented instead, which essentially eliminates the coupling.

In aLIGO, high-quality-factor suspension resonances are damped using shadow sensors [42] with a sensitivity of $2 \times 10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. A global control scheme has been proposed [43] to reduce its direct coupling to the GW output. However, this noise still enters the auxiliary loops and couples to the GW output indirectly. This calls for an improvement of the sensor noise by a factor of 100. Interferometric sensors [44] are promising candidates, and are used in the LIGO-LF design.

Once technical noises are suppressed, LIGO-LF sensitivity will be limited by quantum and thermal noises. Our strategy to improve the fundamental limits is similar to the Strawman Team Red design [45].

Quantum noise [46–48] manifests both as sensor shot noise, and as displacement noise by exerting quantum radiation pressure (QRP) forces on the test masses. LIGO-LF will operate under "resonant-sideband extraction" [49] with the same amount of power circulating in the arms as aLIGO. A signal recycling mirror transmissivity of 0.25 is chosen to optimize the broadband sensitivity.

The quantum noise can be further reduced with squeezed light [50–52]. Here we assume a frequency-dependent squeezing [53–56] that provides 3 dB reduction of the QRP and 6 dB of the shot noise. Relative to aLIGO, QRP is further suppressed by the heavier test masses mentioned above.

Thermal noise [57] from the suspension [36, 58] and the optical coatings [48, 59–62] dominates the sensitivity from 5 to 100 Hz. Suspension thermal noise can be lowered by doubling the length of the last suspension stage to 1.2 m [63, 64] and by applying more sophisticated surface treatments [65]. LIGO-LF's penultimate masses will also need to be suspended with fused silica fibers to avoid excess noise. Furthermore, the vertical suspension resonance can be shifted down to 4.3 Hz by increasing the fiber tension to 1.7 Gpa. Overall, a factor of 5 improvement over aLIGO suspension thermal noise is possible (details of LIGO-LF suspension available in the Supplemental Material, including Refs [66–68]).

The larger test masses and better seismic isolation open up the possibility of increasing spot sizes on the test masses by 50%, with a corresponding reduction in coating thermal noise. Furthermore, a factor of 2 improvement in coating loss angle is expected by the time of LIGO-LF [69].

Further sensitivity improvement below 30 Hz is limited by gravity gradient noise [70–74]. It can be mitigated with offline regression [75], and in our calculation we assume a factor of 10 cancellation [21]. The residual is combined with the residual seismic motion in Fig. 1 under the label 'seismic'.

Scattering is another critical noise source below 30 Hz [22, 76, 77]. A small amount of light can scatter off the test masses due to surface imperfections, hit the baffles along the beam tubes, and finally recombine with the main beam. These stray photons induce differential power fluctuations which perturb the test masses via radiation pressure. In Fig. 1 we present a scattering noise curve estimated from typical ground motion at the LIGO sites with an anticipated 50% improvement in the mirror surface quality relative to aLIGO. As the relative displacement between the test mass and the tube is comparable to the laser wavelength ($1\,\mu$m), the coupling can become nonlinear, up-converting the baffle motion below 0.4 Hz up to 5 Hz [23, 78] . For rare cases where the ground motion is severe, an up-conversion shelf can form [22] and limit the low-frequency sensitivity. The anti-reflection surfaces along the optical path also create scattering noise. To suppress it, baffles should be constructed to block 99.9% of the stray light (details available in the Supplemental Materials with Ref [79].)

Summarizing, the key LIGO-LF advancements consist of low-noise, interferometric sensors for seismic isolation and suspension damping, and heavy test masses with large spot sizes for improving the fundamental limits. The LIGO-LF suspension system is also redesigned. Combined with squeezed light, balanced-homodyne readout, and low-loss coating that are planned for A+, the upgrades leads to the final LIGO-LF sensitivity.

Astrophysical applications.– LIGO-LF can deliver a rich array of science in astrophysics. Here we consider three examples, (*i*) binary BHs, including the expected range of detectability and detection rate, and parameter estimation (PE) of events, (*ii*) binary NSs, focusing on the source localization and the detectability of the tidal excitation of NS r-modes, and (*iii*) the GW memory effect. The technical details are provided in the Supplemental Material with Refs [80–87]. The searches for the stochastic GW background [88] and the continuous GW [89] rely mostly on the instrument's high-frequency performance, and are not enhanced by LIGO-LF.

*(i)–*With the LIGO-LF upgrade, both the maximum detectable distance and mass, and the number of detections are larger than with aLIGO and A+, as illustrated in Fig. 3. In the left we plot the single-detector horizon and range [90] (in both redshift z and luminosity distance $D_{\rm L}$) for binaries with different total masses. The systems are assumed to be non-spinning and to have equal masses. A single LIGO-LF could detect binary BHs to cosmological distances ($z \simeq 6$), whereas a network of 4 detectors would observe to $z \sim 10$, potentially accessing the first generation of stellar BHs [91].

Assuming a power-law mass distribution and a merging rate of $97(1+z)^2\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$ [92, 93], the expected number of detections of coalescing BH binaries is shown in the right of Fig. 3. It predicts that a single LIGO-LF can detect ~ 4000 merging BHs per year, 18 (2.3) times of aLIGO's (A+'s) detection rate. The large number of events observed by LIGO-LF increases the statistical signal-to-noise ratio (SNR), which may be used to separate formation channels that predict different event rates [94, 95], and to constrain the fraction of dark matter in the form of primordial BHs [92, 96].

Moreover, LIGO-LF enables more accurate PE than aLIGO. To emphasize the improved low-frequency sensitivity, we consider binaries with detector-frame total mass $M_{\rm tot}^{\rm (d)} \geq 100\,M_\odot$. Since the sensitivity of A+ and aLIGO are similar below 20 Hz, we consider the comparison between LIGO-LF and aLIGO. Qualitatively, the improvements are due to two facts: more total SNR is accumulated in LIGO-LF than in aLIGO, and the SNR starts to accumulate at lower frequencies. Thus, if aLIGO can only measure the merger-ringdown phase of a coalescence, with LIGO-LF we could access the inspiral phase as well, allowing for a more precise estimation of the component masses and spins.

To quantify these improvements, we simulate GW signals with the `IMRphenomPv2` waveform [97] and in-

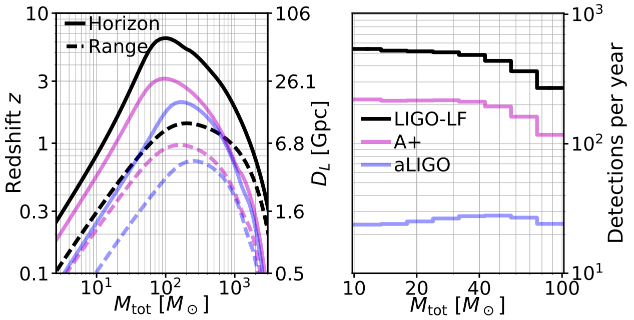

FIG. 3. Left: The horizon (solid) and range (dashed) for binaries with different (source-frame) total masses. A single LIGO-LF may reach a cosmological redshift $z \simeq 6$. Right: expected detections rate of coalescing stellar-mass BH binaries as a function of the total mass. We divide M_1 and M_2 each into 8 logarithmic bins from $10\,M_\odot$ to $100\,M_\odot$ and marginalize over mass ratio to derive the event rate per total mass bin. LIGO-LF can detect ~ 4000 events per year, 18 times more than the expected number for aLIGO. All the numbers are calculated assuming a single detector.

ject them to mock detector noise. We consider 5 total mass bins from $100\,M_\odot$ to $2000\,M_\odot$, each with 3 spin configurations: ($\chi_{\rm eff}$=$\chi_{\rm p}$=0), ($\chi_{\rm eff}$=0.5, $\chi_{\rm p}$=0.6), and ($\chi_{\rm eff}$=$-$0.5, $\chi_{\rm p}$=0.6). Here $\chi_{\rm eff}$ is the mass-weighted sum of component spins along the orbital angular momentum [98, 99], and $\chi_{\rm p}$ captures the precessing components [100]. The effect of mass ratio has been studied in Refs. [11, 12] so we focus on the equal mass case. We consider a 4-detector network formed by the Hanford (H) and the Livingston (L) sites, LIGO-India (I), and aVirgo (V). For HLI, we consider both the LIGO-LF and aLIGO sensitivities; for V, we fix it at its design sensitivity [7]. KAGRA [101] is not included as it is less sensitive to IMBHs. For each source, the inclination is fixed to 30° and the distance is chosen such that the network SNR is 16 with aLIGO's sensitivity. We then use the `LALInference` [102] to get posterior distributions of source parameters. The PE results refer to the detector frame and we denote them with a superscript '(d)'.

In Fig. 4 we plot the 90% credible intervals of the chirp mass $\mathcal{M}_c^{(\rm d)}$, total mass $M_{\rm tot}^{(\rm d)}$, and $\chi_{\rm eff}$. For the masses, we present the results for the non-spinning case. When spins are included, an aligned (anti-aligned) spin tends to improve (degrade) the inference accuracy [103]. Similar effects can also be seen in the posterior distributions of $\chi_{\rm eff}$, as illustrated in the bottom panels. The precession term $\chi_{\rm p}$ cannot be well constrained even with LIGO-LF.

LIGO-LF typically enables a factor of 2 improvement in constraining the sources' redshift compared to aLIGO, limiting the improvement in measuring the source-frame masses to similar level (see the Supplemental Material for the redshift posteriors). The effective spin, nonetheless, is unaffected by the redshift and thus LIGO-LF can achieve 3-5 times better accuracy than aLIGO, which

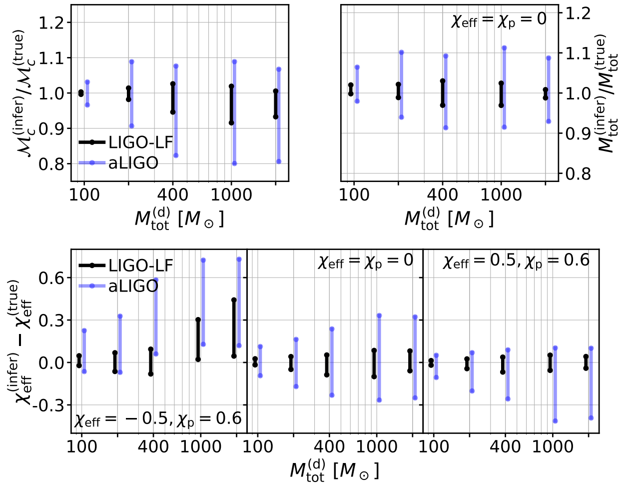

FIG. 4. The 90% credible intervals of the detector-frame chirp mass $\mathcal{M}_c^{(\rm d)}$ (top-left), total mass $M_{\rm tot}^{(\rm d)}$ (top-right), and effective spin $\chi_{\rm eff}$ (bottom) are all significantly smaller for LIGO-LF than for aLIGO. LIGO-LF also reduces biases, especially for $\mathcal{M}_c^{(\rm d)}$ and $\chi_{\rm eff}$ when the spin is anti-aligned (bottom-left).

will be essential for discriminating between different formation scenarios that predict different spin configurations [104, 105].

(ii)–We use the Fisher matrix to examine LIGO-LF's ability to localize a binary NS including effects of the Earth's rotation [106, 107]. We consider the same network as in the PE section. The result is shown in the left panel of Fig. 5. The final localization error in solid angle, $\Delta\Omega_s$, is 3.5 (1.2) times smaller with LIGO-LF than with aLIGO (A+). While LIGO-LF's improvement over A+ is mild when the entire signal is used, it is nonetheless dramatic (a factor of 5 over A+ and 10 over aLIGO) if we use only data below 30 Hz, about 1 min prior the final coalescence. This illustrates LIGO-LF's ability to achieve a more timely localization than A+ and aLIGO.

The r-mode study follows Ref. [108], and we focus on the l=2, m=1 mode. The results are summarized in the right panel of Fig. 5. We find that if the NS spins at a rate greater than 35 Hz [109], a single LIGO-LF may detect the r-mode resonance up to a distance of 50 Mpc. Since the phase shift of the m=1 r-mode depends on the NS stratification which is sensitive to the internal composition and the state of matter [110, 111], a detection may thus place constraints on the NS equation of state from physics beyond the star's bulk properties [112]. Furthermore, the r-mode resonance provides an independent measurement of the NS spin, which may help breaking the spin-mass ratio degeneracy [14] and improve the accuracy in measuring the (equilibrium) tidal deformability [15, 113].

(iii)–We consider the GW memory effect [114] adopting the minimal-waveform model [115]. The result is shown in Fig. 6. Together with the increased detection

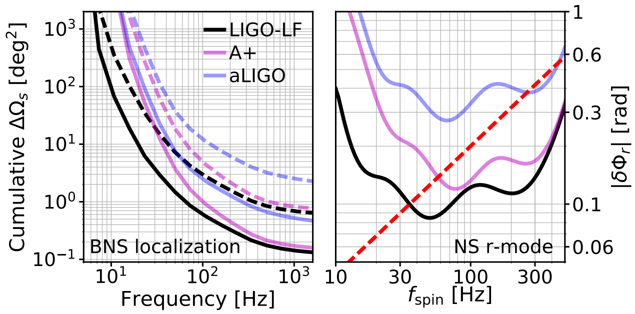

FIG. 5. Left: The cumulative uncertainty in localization, $\Delta\Omega_s$, for the HLIV network. We consider NS binaries at the Coma cluster with two inclinations, 30° (solid) and 75° (dashed), and marginalize over the polarization and time of arrival. LIGO-LF improves the localization by a factor of 3.5 over aLIGO using the entire signal, and by a factor of 5 over A+ using only the sub-30 Hz data. Right: The uncertainty (solid) in measuring the phase shift due to resonant excitation of the NS r-mode, $\delta\Phi_r$, as a function of the NS spin frequency, $f_{\rm spin}$. We consider the single detector case and fix the sources at 50 Mpc with optimal orientation. Also shown in the red-dashed line is the expected physical r-mode phase shift. The effect is detectable when the real phase shift is greater than the statistical error.

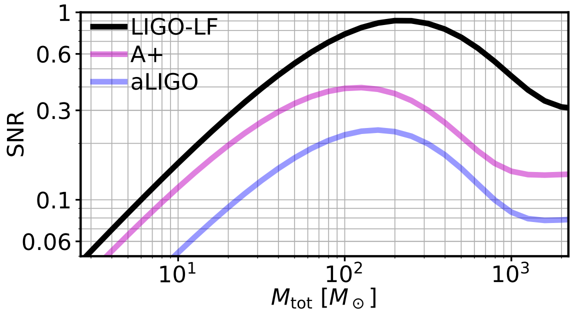

FIG. 6. SNR from the GW memory effect as a function of the source-frame total mass. The sources are fixed at $z = 0.1$ and inclination of 30°. The peak SNR seen in LIGO-LF is 4 (2) times greater than that seen in aLIGO (A+).

rate, LIGO-LF has a promising probability to detect this effect via event-stacking [116].

Conclusions.– In this Letter we propose LIGO-LF, an upgrade improving aLIGO's low-frequency performance. The new technologies required for this update are directly applicable to the future generation of detectors. Comparing LIGO-LF to aLIGO, the mass and spatial range of binary BHs detectable are greatly enhanced, and the localization of NS binaries can be achieved at an much earlier time in the, enabling more timely follow-up.

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