FIG. 3.   Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). *Inset (a):* Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). *Inset (b):* The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain amplitude. The sensitivity is limited by photon shot noise at frequencies above 150 Hz, and by a superposition of other noise sources at lower frequencies [47]. Narrow-band features include calibration lines (33–38, 330, and 1080 Hz), vibrational modes of suspension fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

the gravitational-wave signal extraction by broadening the bandwidth of the arm cavities [51,52]. The interferometer is illuminated with a 1064-nm wavelength Nd:YAG laser, stabilized in amplitude, frequency, and beam geometry [53,54]. The gravitational-wave signal is extracted at the output port using a homodyne readout [55].

These interferometry techniques are designed to maximize the conversion of strain to optical signal, thereby minimizing the impact of photon shot noise (the principal noise at high frequencies). High strain sensitivity also requires that the test masses have low displacement noise, which is achieved by isolating them from seismic noise (low frequencies) and designing them to have low thermal noise (intermediate frequencies). Each test mass is suspended as the final stage of a quadruple-pendulum system [56], supported by an active seismic isolation platform [57]. These systems collectively provide more than 10 orders of magnitude of isolation from ground motion for frequencies above 10 Hz. Thermal noise is minimized by using low-mechanical-loss materials in the test masses and their

suspensions: the test masses are 40-kg fused silica substrates with low-loss dielectric optical coatings [58,59], and are suspended with fused silica fibers from the stage above [60].

To minimize additional noise sources, all components other than the laser source are mounted on vibration isolation stages in ultrahigh vacuum. To reduce optical phase fluctuations caused by Rayleigh scattering, the pressure in the 1.2-m diameter tubes containing the arm-cavity beams is maintained below 1 μPa.

Servo controls are used to hold the arm cavities on resonance [61] and maintain proper alignment of the optical components [62]. The detector output is calibrated in strain by measuring its response to test mass motion induced by photon pressure from a modulated calibration laser beam [63]. The calibration is established to an uncertainty (1σ) of less than 10% in amplitude and 10 degrees in phase, and is continuously monitored with calibration laser excitations at selected frequencies. Two alternative methods are used to validate the absolute calibration, one referenced to the main laser wavelength and the other to a radio-frequency oscillator