Snowmass2021 - Letter of Interest

Probing Dark Energy with Gravitational Wave Standard Sirens in the HEP Experimental Cosmic Frontier

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract

The expansion rate of the Universe today, H_0, as measured by several complementary probes, is a point of tension in the field of cosmology[1]. Standard siren measurements of H_0 — the practice of combining the luminosity distance of a compact object merger obtained from the gravitational wave (GW) amplitude with a redshift obtained from electromagnetic (EM) follow-up observations — offer a probe of cosmic acceleration that is independent from both the traditional distance ladder or sound horizon measurements that are currently in tension[2 3 4]. With new and improved GW detectors coming online in the next decade[5 6 7 8], several hundred binary neutron star (BNS) mergers will be detectable, and tight H_0 constraints will be possible if the EM community has the necessary instruments to measure the redshift of the merger. In practice, several dozen potential optical counterparts to GW mergers can be found during real-time photometric follow-up observations by optical imagers; the task of confirming the candidates as the true counterpart of the GW and of measuring the redshift falls on spectroscopic instruments. In the remainder of this letter, we describe the necessary components of a spectroscopic instrument that can enable standard siren techniques to deliver one-percent statistical precision on H_0 by the year 2030. We argue that this technique of measurement of H_0 be considered by the HEP Cosmic Frontier community as an integral part of the program to discover the nature of dark energy. In particular for the next 10 year time frame, this precision can be accomplished by leveraging existing and planned survey instruments, as described in this letter. Our estimates of the impact of standard sirens for the dark energy program are based on the experience acquired in the past three observing campaigns with the Dark Energy Survey (DES) Gravitational Waves project (DESGW) project, which produced the most comprehensive counterpart searches to date[9 10], successfully discovered the EM counterpart of GW170817[11], and led early measurements of H_0 using the standard sirens method[3 4].

Gravitational Wave Counterpart Searches in the Coming Decade

In the upcoming fourth observing run (O4) of the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo Observatory, the Kamioka Gravitational Wave Detector (KAGRA)[12] is set to join the network. LIGO-India is on track to join the network for O5 near the start of 2024. This expanded network expects sensitivity to BNS mergers up to distances of 330 Mpc and localization areas ranging from 3.0-30.0 sq. deg. depending on the signal-to-noise of the GW detection[6,13]. At these distances, a GW170817-like counterpart would have an r-band magnitude of $m_r = 21.8$ mag, meaning that large aperture wide-field optical imagers like the Rubin Observatory LSST Camera and the Dark Energy Camera (DECam)[14] at Cerro Tololo Inter-American Observatory will have little difficulty covering the full-localization area and detecting the GW counterpart photometrically. Based on real-time follow-ups by DECam in O3[15,9,10], the most comprehensive follow-up analyses to date, potential optical counterparts are detected at a rate of approximately 1.24 per night per sq. deg., meaning dozens of objects will require spectroscopic characterization to confirm the true counterpart. Therefore, it is essential that the spectroscopic resources in the southern hemisphere can systematically characterize several $m_r = 22$ mag objects each night.

A New Spectroscopic Instrument

Current spectroscopic instruments in the southern hemisphere do not meet these requirements. Slit-based spectrographs like The Southern Astrophysical Research (SOAR) Telescope[16] and The Southern African Large Telescope (SALT)[17] are unable to target more than a handful of counterpart candidates each night. Fiber-based spectrographs like the Dark Energy Spectroscopic Instrument (DESI)[18,19] and 4-metre Multi-Object Spectroscopic Telescope (4MOST)[20], while capable of targeting hundreds of objects each night, at present are not mounted on telescopes with large enough apertures to detect optical counterparts to BNS mergers at their expected distances. We estimate that incorporating future GW events into the portfolio of dark energy observables will require an instrument consisting of a fiber-based spectrograph mounted on a 6m or larger telescope with a dedicated Target of Opportunity (ToO) program for GW counterpart characterization. Some of the already proposed southern hemisphere experiments that would be a close match to these requirements are SpecTel[21] and MegaMapper[22]. These fiber-based instruments will both utilize large apertures and wide fields of view, ideal for GW counterpart targeting. A dedicated ToO program for GW counterpart characterization on a powerful spectroscopic instrument will enable standard sirens to be a competitive cosmological probe over the next decade.

The Future of Standard Siren Science

To assess the constraining power on H_0 that a 6m or larger, fiber-based southern hemisphere spectroscopic telescope will produce from GW counterpart characterization, we perform a Monte-Carlo forecasting of this instrument compared to other spectroscopic instruments. We assume an astrophysical BNS merger rate of 900 mergers per Gpc^3 per year — well within the upper limit on this rate from O1[23] and consistent with the detected BNS mergers in O2 and O3. We then simulate GW alerts at distances detectable by the 4 detector network of LIGO-Livingston, LIGO-Hanford, Virgo, and KAGRA (HLVK). Once enough time has passed in the simulation for LIGO-India to come online, we base the simulated alerts on the HLVKI network. From the simulated distance of each alert, we assume a reasonable signal-to-noise of the gravitational wave and obtain the expected localization area from previous forecasts of GW detector sensitivity[13]. We then assume a number of counterpart candidates detected by photometric methods and in need of spectroscopic characterization to be proportional to the localization area, at a rate of 1.24 candidates per sq. deg, where this rate is derived from the DECam follow-up of GW190814[24,25]. We also calculate an expected r-band magnitude of the true counterpart by assuming a GW170817-like r-band luminosity. At this stage, we have all the information necessary to assess whether a spectroscopic instrument will be able to confirm a counterpart: if the limiting r-band magnitude of the instrument is sufficient to detect the simulated true counterpart, then the probability of the instrument detecting the counterpart is the number of objects the instruments can

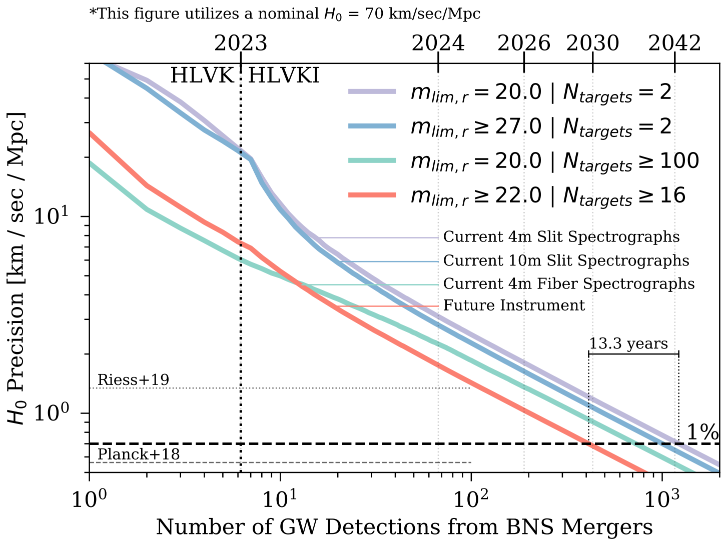

Figure 1: Projections of statistical H_0 precision from standard siren measurements. We characterize spectroscopic instruments by their limiting r-band magnitude $m_{lim,r}$ and the number of candidates they can target in a single night $N_{targets}$. The GW detector network consists of HVLK before 2023 and HVLKI after the start of O5 at the end of 2023. Given predicted rates of GW detections from BNS mergers and assumptions about the number and brightness of EM counterpart candidates motivated by O3, we find that a spectroscopic instrument with $m_{lim,r} = 22.0$ and $N_{targets} = 16$ will reach one-percent statistical precision on H_0 by 2030, up to 13.3 years faster than current instruments. Furthermore, we find that increasing $m_{lim,r}$ or $N_{targets}$ beyond these values returns no significant improvement in the ability to constrain H_0 with standard sirens.

target in a single night divided by the number of candidates (with an implicit ceiling at unity).

With each new GW detection, the H_0 uncertainty decreases as $1/\sqrt{N}$ where N is the number of BNS mergers[26]. Figure 1 shows how the statistical precision on H_0 is expected to shrink over the next 20 years from standard siren techniques under the conditions of different spectroscopic instruments as a result of their ability or inability to confirm the true counterparts of the simulated GW alerts. Using current 4m and 10m slit spectroscopic telescopes, we expect the statistical H_0 uncertainty to reach one-percent precision by 2043. These instruments are limited by not being able to characterize a high percentage of candidates for each alert. Similarly, by using current 4m fiber spectrographs, we are only able to reach this uncertainty by the late 2030s. This class of instrument is limited by depth, since true counterparts are expected to be near $m_r = 22.0$ mag with the increased range of HLVKI. Our proposed instrument, a 6m or larger telescope with a fiber-based specrograph, will be capable of detecting objects at the expected magnitude of the GW counterparts while simultaneously targeting sufficiently high fractions of the total number of candidates per night. This configuration reaches one-percent precision on H_0 by 2030, up to 13.3 years faster than current spectroscopic instruments. Furthermore, we find that a spectroscopic instrument that can probe deeper than $m_r = 22.0$ mag or target more than 16 objects per night will constrain H_0 no more rapidly than our proposed instrument: this cap on the statistical uncertainty is determined by the detection limits of the HLVKI network.

Conclusion

The community is gearing up for next generation facilities including spectroscopic instruments for dark energy. In this letter we present the requirements of a spectroscopic instrument that will be essential to achieve the broader goals of interest for the cosmic frontier in multi-messenger physics[27]. Additionally, we make the case for including standard sirens as a key component of the science goals of future experiments from the beginning, ensuring that their design (e.g. telescope aperture and multi-object capability) and survey strategy parameters (e.g. a dedicated GW ToO program) meet the requirements to optimally extract the cosmology information from GW standard sirens and advance towards resolving the dark energy problem.

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