Snowmass2021 - Letter of Interest

Dark Energy Science with Multimessenger Probes and the Vera Rubin Observatory's Legacy Survey of Space and Time

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 Rubin Observatory is a powerful discovery machine for gravitational wave (GW) sources. We describe a multimessenger cosmology program aiming to perform precise and accurate — percent level, or better — cosmological measurements using hundreds of mergers of binary neutron stars and black holes as standard sirens. In the LSST-era the rate of binary neutron star (BNS) mergers detected by the gravitational wave observatories (LIGO, Virgo and KAGRA) is expected to be 100/year. The LSST will be used in a target of opportunity observations mode to identify the electromagnetic counterparts of merger events triggered via their gravitational wave emission. The search requires template LSST data; the discovery places a premium on complementary spectroscopic observations to obtain the redshift information that combines with the distance information to enable the cosmology analysis. Increases in sample size and data quality over the next decade will enable multimessenger probes to become a key component of the dark energy science program in the time frame considered by the Snowmass community planning process. We therefore argue that this science case be incorporated to studies led by the topical groups within the Cosmic Frontier, particularly focusing on establishing the ecosystem of coordinated facilities required to unlock the full potential of multimessenger probes for dark energy science.

From the Hubble constant to dark energy with standard sirens

Compact object binary mergers are novel promising probes of cosmology. Often referred to as standard sirens, such events are multimessenger probes: gravitational waves emitted in the last moments of the inspiral are used to determine their absolute distances, while their redshifts are determined via traditional astronomical observations. They are distance indicators analogous to type-Ia Supernovae which are standard candles. The main motivation to pursue standard sirens for cosmology is that, contrary to Supernovae, their distances are determined from first principles, without the need of multiple astrophysical calibration steps that introduce challenging systematic uncertainties.

Of the several key parameters of modern cosmology, distance indicators are particularly sensitive to the expansion history of the Universe as a function of redshift, the Hubble parameter $H(z)$. Nearby sources, in particular, are used to measure the current rate of expansion, $H_0 \equiv H(z=0)$.

A breakthrough in understanding the physics of dark energy is a core goal of our community. Hypothesized to explain the accelerated expansion of the cosmos at redshift $z \lesssim 0.7$, dark energy is an unknown fundamental component of the present Universe. The absolute value of the expansion rate is important: percent-level precision measurements of H_0 are required to cease being a limiting factor on dark energy model limits.

Compared to the well-established cosmology probes such as supernovae, the emerging field of multimessenger cosmology with gravitational waves is advancing in leaps. Since the first observation[1] of a compact binary system merger by the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo Collaboration (LVC), less than five years ago, over 60 merger candidates have been reported, one has had its electromagnetic counterpart identified[2–4], and three have been used for measurements of H_0 with uncertainty of $\sim$14%[5–7]. As the detector network continues to improve the sample sizes are expected to grow exponentially in the coming decade. The ambitious goal of percent-level H_0 measurements from standard sirens is therefore within reach.

Rubin Observatory's Legacy Survey of Space and Time Dark Energy Science Collaboration

The Rubin Observatory Legacy Survey of Space and Time (LSST[8,9]) will run for 10 years. The survey will cover $\approx 18,000$ sq-degrees of southern sky, in 0.7" seeing through u,g,r,i,z filters, using a 9.6 sq-degree camera that in survey mode covers 840 sq-degrees/hour. Each field is imaged roughy 80 times per year. The planning in 2020 is to allocate 5-10% of the observing time to special cadence mini-surveys, including deep fields. This time will include target of opportunity (TOO) visits for high impact observations.

The Dark Energy Science Collaboration (DESC[10,11])) is the international science collaboration, with support from both the DOE and foreign partners, including funding agents in the UK and France, that will make high accuracy measurements of fundamental cosmological parameters using data from the LSST, including TOO observations.

The Gravitational Wave Observatories during the LSST era

During this LSST era we can expect the LIGO/Virgo system of gravitational wave observatories[12] to reach design sensitivity (2021), upgrade to A+ ($\sim$ 2024). machine to start. It is likely that in the later years of the LSST, the space-based antena LISA[13] and the next generation ground-based experiment Cosmic Explorer will begin operating. At design sensitivity LIGO finds NS-NS mergers out to 190 Mpc, VIRGO reaches 125 Mpc, and the soon to come-on-line Kagra reaches 140 Mpc. A LIGO installation in India is planned to operate in 2024 with 190 Mpc. The upgrade to LIGO, A+, planned for 2024, should reach 325 Mpc[14 15]. Thus we can expect in 2025 to be hearing $\sim$ 100 binary neutron star mergers a year. By 2030, improvements to A+ may allow it to reach 1 Gpc for neutron-star mergers, and $z = 1$ for stellar mass black hole binaries.

Percent-level H_0: DESC, LSST, and joint GW-EM astronomy

We are interested in the cosmic siren measurements of the Hubble Constant in the local universe as there is considerable tension between the local and global measurements of this parameter. On the LSST side, as the wide-deep survey is not very efficient for GW event followup, the TOO program will have to be designed to mesh well with the main survey. But a powerful cosmological constraint will not spring from serendipitous discoveries alone. Pursuing this new technique of measuring cosmology will require a dedicated well designed program, relying on several factors:

- **Spectroscopic support to classify candidate counterparts and provide redshift information for cosmology analyses.**
    - *Spectroscopic followup of candidate counterparts* enables rapid false positive rejection during the search and discovery phase, which will be critical to ensure purity of the sample and an efficient use of telescope time.
    - *Spectroscopic followup of galaxies* in the region of interest of GW events will provide redshifts of bright sirens and of likely hosts of dark sirens.
    - Existing and upcoming spectroscopic facilities can be leveraged for this purpose, by implementing a followup TOO program. *Additional specialized spectroscopic resources should also be considered to pull the full power from the technique*.
- **Sustained investigation into the use of both bright and dark sirens to measure cosmological parameters with careful treatment of systematic uncertainties.**
    - This new window certainly has fewer sources of systematic error than methods that measure distances via cepheid stars, BAO feature in the galaxy distribution, or forward modeling the CMB. Yet there is much to be learned from the way uncertainties are treated for those mature cosmology probes.
    - With hundreds of events per year, statistically significant samples will be available. Uncertainties in redshifts, selection effects, and clustering of host galaxies are some of the effects to be quantified in order to ensure we continue to operate in the statistics dominated regime.
- **Coordination of multiple facilities to form an ecosystem optimized for dark energy science with standard sirens.**
    - While progress has been made towards cooperation (e.g., DES/LVC joint analayses of GW170817 and GW180814), cosmic surveys operate separately from the GW experiments. *Full realization of the potential of this new cosmological probe will require closer coordination* between them.
    - Many groups outside of formal collaborations use their telescopes to search for counterparts. Initiatives such as “TreasureMap” enable the community to report observations. *Further coordination with those groups will greatly increase the efficiency of the program.*
    - Several spectrograph-equipped telescopes can be used for followup. *Coordination of these non-DESC resources is essential for the success of the program.*

Conclusion

Exploiting standard sirens to their fullest potential for dark energy science will require a coordinated effort including EM and GW facilities. In the coming decade, DESC can play a leadership role, acting as a focal point for the EM-side of the GW-EM multimessenger cosmology community and setting the stage for larger scale projects beyond the decade. While the investment in such a program is small compared to the initial investment on each facility, the scientific impact is huge. By measuring H_0 with percent-level precision with standard sirens, we will enable a new breakthrough in dark energy model constraints.

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