Hubble's Constant with GW170817 Standard Siren and GW190814 Dark Siren

Rajesh Kumar Dubey[1], Shankar Dayal Pathak[2]

[1,2] Lovely Professional University, Phagwara, Punjab, India

ABSTRACT

The local universe expansion rate is one of the most fundamental and essential cosmological parameters. This value which is known by the name of Hubble's Constant is scientifically measured by electromagnetic sources called distance ladder. Surprisingly, using Gravitational Wave (GW) analysis this value can be measured making GW sources another significant method to act as standard sirens with their electromagnetic counterparts from their host galaxy. The gravitational wave event GW 170817 was the outcome of the merger of two different neutron stars. The electromagnetic event was recorded from the host galaxy NGC4993. The GW170817 has been a considerable success in this direction measuring the value of universe acceleration $H_0 = 70.0^{+12.0}_{-8.0}$ kms^{-1} Mpc^{-1}. Another event in this series GW190817 is Compact Binary Coalescence involving a 22.2 ~ 24.3 M_o. The EM counterpart of this event is unknown so far and hence the event is named Dark Siren. The Hubble's value proposed with this even is close to $H_0 = 75^{+59}_{-13}$ km s^{-1}Mpc^{-1} .The source GW190814 which involves a massive black hole and the other compact object as the lightest black hole or the heaviest neutron star was localized to 18.5 deg^2 at a distance of Mpc.

MOTIVATION

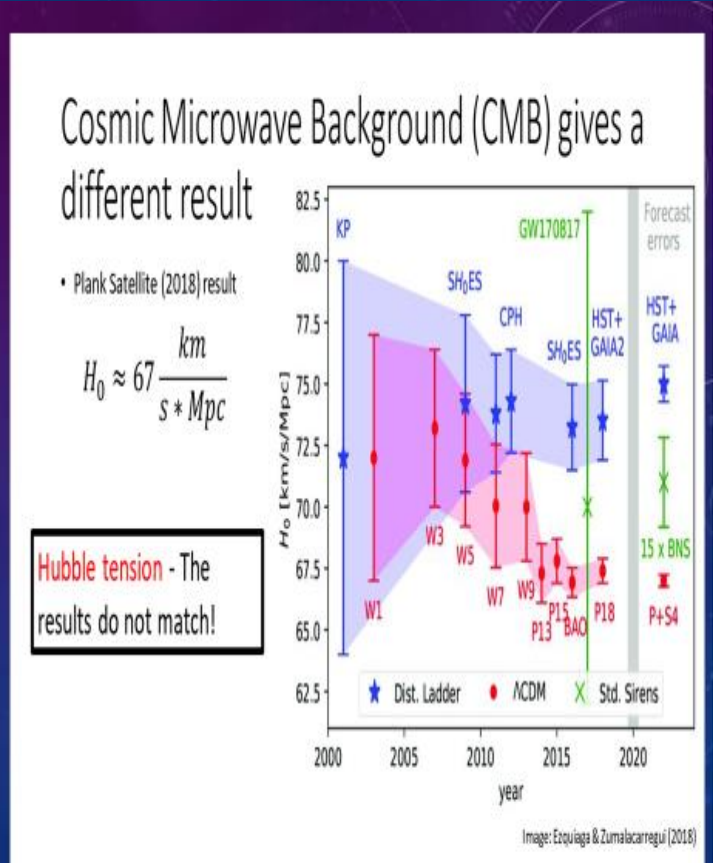
Significant, Unresolved Puzzle of Cosmology.

- Nearly 90 years of a Ground Breaking Discovery- Universe is Expanding
- Revolutionised the theory of Big Bang for its origin and evolution
- Current *rate* of expansion, equal to the constant of proportionality in Hubble's linear relationship
- H_o- The Hubble's Constant is now one of the main pillars in Cosmology
- Different scientific methods adopted for the measurement
- Gravitational Waves Standard Siren and Dark Siren can now play an important role

Wide Range of Methods for Measuring H_0

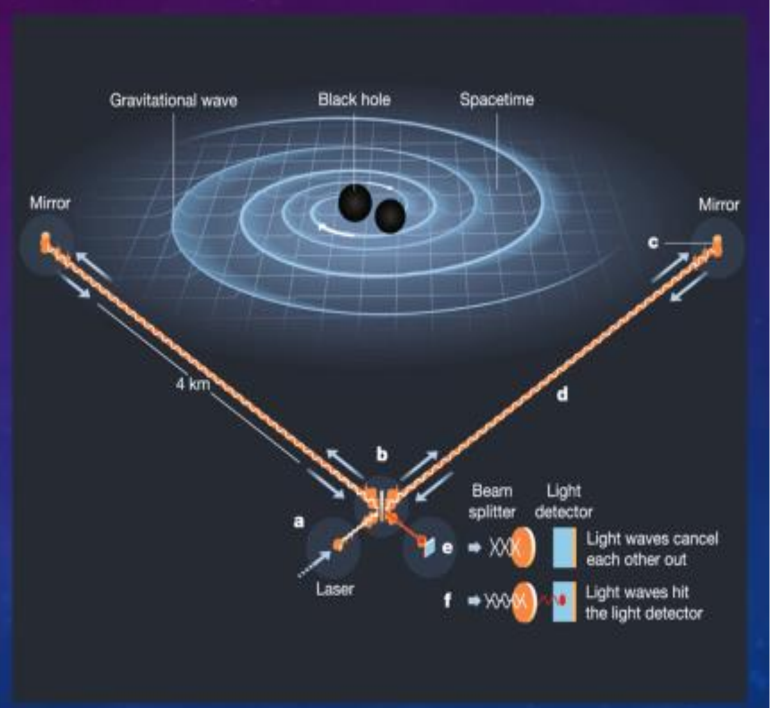
(Model Dependent and Model in-dependent)

- Observations of Cepheid Variable
- Observations of Type-1a Supernovae
- By Tully Fisher Relation (TFR)
- Using Cosmic Microwave background (CMB)
- HST OBSERVATIONS OF CEPHEIDS IN THE SHoES PROGRAM
- Cosmic Distance Ladder



A NEW APPROACH - GW STANDARD SIREN

- ✓ An independent measurement even without an electromagnetic counterpart
- ✓ Provide pure distance measurement avoiding complex astrophysical distance ladder
- ✓ They are directly calibrated by theory
- ✓ Coalescing neutron binaries are a great source
- ✓ They emit both light and gravitational waves
- ✓ Test of General Relativity
- ✓ Can measure both redshift and distance simultaneously
- ✓ Z using optical telescopes
- ✓ R using Gravitational Waves

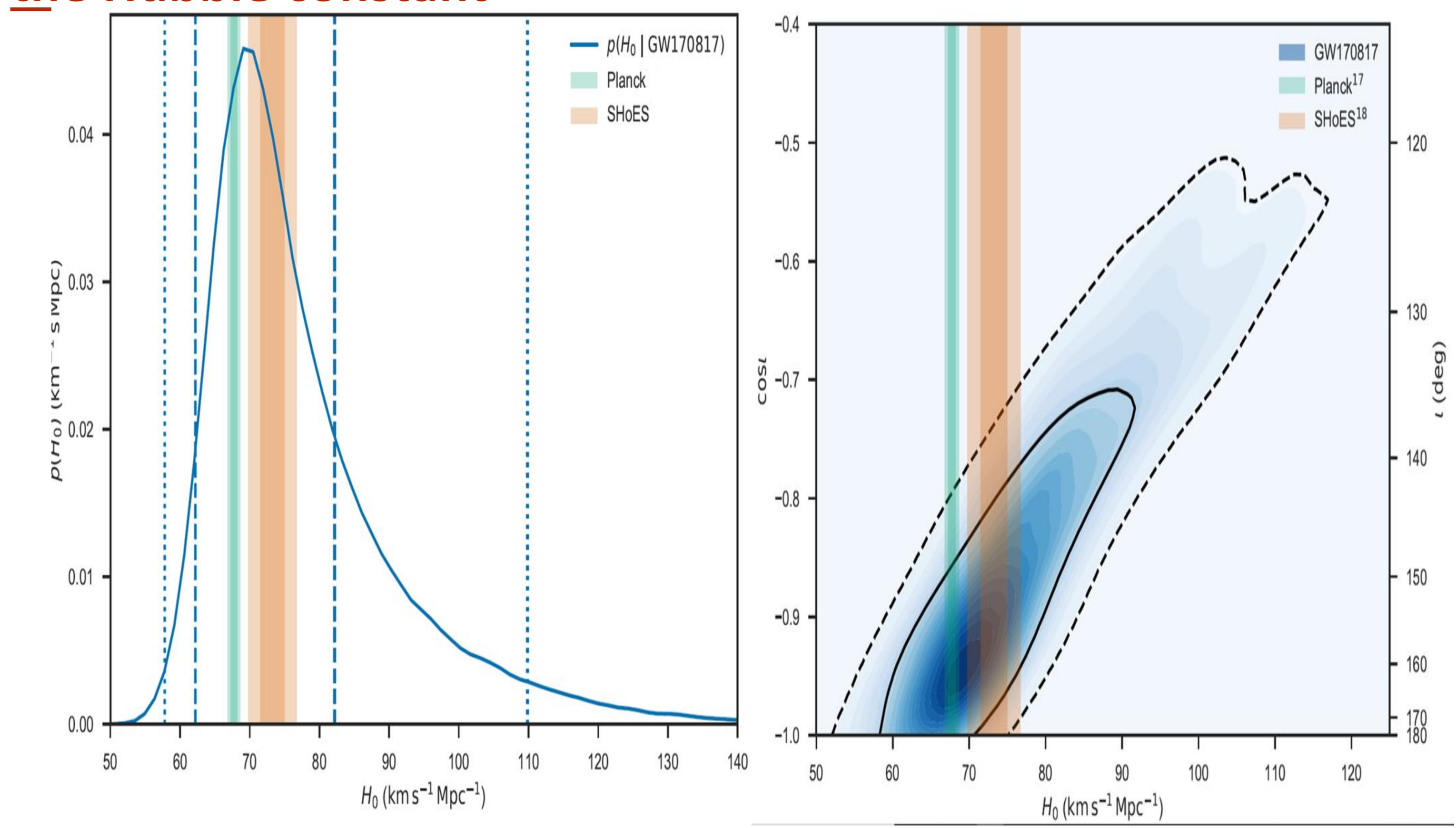


➤ **Motivation for the Standard Sirens** for Hubble constant using GW

Methods and Observations

- ➤ Unlike most extragalactic distance observables, mergers of neutron star and black hole binary systems are absolute distance indicators.
- ➤ Often referred to as "standard sirens," they emit gravitational waves (GWs) from which the luminosity distance can be inferred without relying on any calibration with respect to another source: the rate of change in frequency gives the system's size and thus the intrinsic amplitude, which is compared against the observed signal amplitude to obtain the distance to the source.
- ➤ If redshifts are associated with those sirens (in the simplest case, the host galaxy is identified and its redshift is obtained via spectroscopic follow up), a measurement of the present rate of expansion of the universe H_o can be achieved via the distance – redshift relation. The use of GW sources as cosmological probes was first proposed by Schutz (1986), and recently revisited in several works (e.g., Holz & Hughes 2005).
- ➤ LIGO and/or VIRGO gravitational-wave measurements of coalescing, neutron-star-neutron-star (NS-NS) binaries and black-hole-neutron-star (BH-NS) binaries at cosmological distances to determine the cosmological parameters of our Universe.
- ➤ From the observed gravitational waveforms one can infer, as direct observables, the luminosity distance D of the source and the binary's two "redshifted masses,"
- ➤ $M'_1 = M_I(1 + r)$ and $M'_2 = M_2 (1 + z)$: where M_i are the actual masses and $z = \frac{\Delta\lambda}{\lambda}$ is the binary's cosmological redshift.
- ➤ Assuming that the NS mass spectrum is sharply peaked about $1.4M_\theta$, as binary pulsar and x-ray source observations suggest, the redshift can be estimated as $z = M_{NS}/l.4M_\theta - 1$.
- ➤ The actual distance-redshift relation D(z) for our Universe is strongly dependent on its cosmological parameters
- ➤ [the Hubble constant H_o, or h_o = Ho/100 km s^{-1}Mpc^{-1}, the mean mass density ρ_m or
- ➤ Density parameter $\Omega_0 = \left(\frac{8\pi}{3H_0^2}\right)\rho_m$, and the cosmological constant Λ, or $\lambda_0 = \frac{\Lambda}{3H_0^2}$: so by a statistical study of (necessarily noisy) measurements of D and z for a large number of binaries, one can deduce the cosmological parameters.

GW170817 Standard Siren Plot summarising the inference on the Hubble constant



- ➤ The optical counterpart to GW170817 was found within 10 arcseconds of the center of the galaxy NGC 4993, an angle that corresponds to a separation of about 2 kpc. The redshift of the galaxy is 0.009
- ➤ A Bayesian analysis that combines the galactic redshift with the LIGO–Virgo measurement of distance to GW170817 leads to an estimate of the value of the Hubble constant: $H_0 = 70^{+12}_{-8}$ km s^{-1} Mpc^{-1}. Figure shows the full Bayesian probability distribution for H_0.
- ➤ The blue curve shows the probability distribution for the value of H_0, as determined from measurements of the event GW170817. Plot summarising the inference on the Hubble constant. The relative probability of different values of H_0 is represented by the solid blue curve, which peaks at 70 kms^{-1} Mpc^{-1}.
- ➤ The dashed and dotted blue vertical lines respectively show the limits of 68.3% and 95.4% credible intervals for H_0.
- ➤ The vertical green and orange bands represent the constraints on H_0 from two state-of-the-art analyses using solely electromagnetic data
- ➤ The green bands show the range of values inferred from analysis of CMBR data obtained by the Planck satellite

SIREN GW190814- Best Localized Dark Siren

- ➤ The gravitational-wave signal, GW190814, was observed during LIGO's and Virgo's third observing run on August 14, 2019 at 21:10:39 UTC
- ➤ Compact Binary Coalescence involving a 22.2 – 24.3 Solar Masses Black hole and a compact object with a mass of 2.50 – 2.67 Solar Masses (all measurements quoted at the 90% credible level).
- ➤ Has a signal-to-noise ratio of 25 in the three-detector network.
- ➤ The source was localized to 18.5 deg^2 at a distance of 241^{+41}_{-45} Mpc
- ➤ No electromagnetic counterpart has been confirmed to date.
- ➤ The source has the most unequal mass ratio yet measured with gravitational waves, $0.112^{+0.008}_{-0.009}$
- ➤ Secondary component is either the lightest black hole or the heaviest neutron star ever discovered in a double compact-object

For a fixed reference cosmology (Ade et al. 2016), the GLADE galaxy catalog (Dálya et al. 2018) is approximately 40% complete at the distance of GW190814 and contains 472 galaxies within the 90% posterior credible volume of GW190814.

- ➤ To obtain a constrain on H_0, the methodology described in Abbott et al. (2019c) and the GLADE catalog is used.
- ➤ Take a flat prior for $H_0 \in [20, 140]$ km s–^{1} Mpc^{-1} and assign a probability to each galaxy that it is the true host of the event that is proportional to its B-band luminosity.
- ➤ Using the posterior distribution on the distance obtained from the combined PHM samples, it is obtain $H_0 = 75^{+59}_{-13}$ km s^{-1}Mpc^{-1}using GW190814 alone (mode and 68.3% highest posterior density interval; the median and 90% symmetric credible interval is $Ho = 83^{+55}_{-53}$ km s^{-1} Mpc^{-1}),

which can be compared to $H_0 = 75^{+40}_{-32}$ km s^{-1} Mpc^{-1} (Soares-Santos et al. 2019) obtained using the dark siren GW170814 alone

Conclusions and Future Prospects

1) In the future, we will have more low-redshift sta.dard siren data, and so the error will be reduced to 15%/ *N*, with *N* being the number of low-redshift standard siren data. Therefore, if we have 50 data, then the error will be decreased to about 2% , similar to the error of the current distance ladder result. Actually, in the near future, the KAGRA and LIGO-India will join the detector network, and thus the error will become smaller, around 13%/ *N*

2) n 2023, about 50 events will be ob- served by the Advanced LIGO-Virgo network and 2% error will be achieved; in 2026, about 100 events will be observed by the five detectors and about 1% error will be achieved.