Universe Acceleration by Gravitational Waves
Standard Siren and Dark Siren

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Physical Interpretations of Relativity Theory (PIRT-2021), Moscow, Russia
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
- $H_0$- 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
In the 1920s Georges Lemaître and Edwin Hubble made the discovery that our universe is expanding.

Schematic plot of the Hubble relation, adapted from Edwin Hubble's original 1929 data.

The linear relationship between radial velocity (vertical axis, wrongly labelled in kilometres in Hubble’s original paper) and distance (horizontal axis, labelled in parsecs) is clearly apparent – although there is considerable scatter in the data and the distance range extends to only about 2 Mpc.

Over Estimated Value

Hubble's original estimate for $H_0$ was about 500 kms$^{-1}$ Mpc$^{-1}$
WIDE RANGE OF METHODS FOR MEASURING $H_0$

➤ 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
DIFFERENT VALUES FOR $H_0$

- Planck
- WMAP9
- Cepheids+SNela
- Carnegie HP
- HST Key Project
- UGC 3789
- RXJ1131-1231
- SZ clusters

Uses three 1st-rung calibrators: 71.3 – 75.7

UGC, at 50 Mpc: now $H_0 = 68.9 \pm 7.1$
➢ A 2.4% DETERMINATION OF THE LOCAL VALUE OF THE HUBBLE CONSTANT (Riess et al 2016)

➢ One of the best results from Riess A G, Macri L M 2016

➢ Used the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST)

➢ Best estimate of 73.24 ± 1.74 km/sec/Mpc combines the anchors NGC4258, MW, and LMC

➢ Includes systematic errors for a final uncertainty of 2.4%.

Figure 1. Uncertainties in the determination of \( H_0 \). Uncertainties are squared to show their individual contribution to the quadrature sum. These terms are given
One of the best results from Riess A G, Macri L M 2016

Used the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST)

Best estimate of $73.24 \pm 1.74$ km/sec/Mpc combines the anchors NGC4258, MW, and LMC

Includes systematic errors for a final uncertainty of 2.4%.

<table>
<thead>
<tr>
<th>Anchor(s)</th>
<th>Value $(\text{km s}^{-1} \text{Mpc}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>One Anchor</strong></td>
<td></td>
</tr>
<tr>
<td>NGC 4258: Masers</td>
<td>72.25 $\pm$ 2.51</td>
</tr>
<tr>
<td>MW: 15 Cepheid Parallaxes</td>
<td>76.18 $\pm$ 2.37</td>
</tr>
<tr>
<td>LMC: 8 Late-type DEBs</td>
<td>72.04 $\pm$ 2.67</td>
</tr>
<tr>
<td>M31: 2 Early-type DEBs</td>
<td>74.50 $\pm$ 3.27</td>
</tr>
<tr>
<td><strong>Two Anchors</strong></td>
<td></td>
</tr>
<tr>
<td>NGC 4258 + MW</td>
<td>74.04 $\pm$ 1.93</td>
</tr>
<tr>
<td>NGC 4258 + LMC</td>
<td>71.62 $\pm$ 1.78</td>
</tr>
<tr>
<td><strong>Three Anchors (Preferred)</strong></td>
<td></td>
</tr>
<tr>
<td>NGC 4258 + MW + LMC</td>
<td>$73.24 \pm 1.74$</td>
</tr>
<tr>
<td><strong>Four Anchors</strong></td>
<td></td>
</tr>
<tr>
<td>NGC 4258 + MW + LMC + M31</td>
<td>73.46 $\pm$ 1.71</td>
</tr>
<tr>
<td>Optical only (no NIR), three anchors</td>
<td></td>
</tr>
<tr>
<td>NGC 4258 + MW + LMC</td>
<td>71.56 $\pm$ 2.49</td>
</tr>
</tbody>
</table>
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

Cosmic Microwave Background (CMB) gives a different result

- Plank Satellite (2018) result

$$H_0 \approx 67 \frac{km}{s \cdot Mpc}$$

Hubble tension - The results do not match!
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
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 $H_0$ 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,"

$M'_1 = M_1 (1 + r)$ 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 $1.4M_\odot$, as binary pulsar and x-ray source observations suggest, the redshift can be estimated as $z = \frac{M_{NS}}{1.4M_\odot} - 1$. 
The actual distance-redshift relation $D(z)$ for our Universe is strongly dependent on its cosmological parameters.

The Hubble constant $H_0$, or $h_0 = H_0/100 \text{ km s}^{-1}\text{Mpc}^{-1}$, the mean mass density $\rho_m$ or

Density parameter $\Omega_0 = \left(\frac{8\pi}{3H_0^2}\right)\rho_m$, and the cosmological constant $\Lambda$, 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.
Distance: determined from the gravitational waves

- From general relativity quadrupole formula for amplitude, frequency:

\[ r = C f^{-2} \langle h \rangle^{-2 \tau}^{-1} \]

- \( f \) = grav. wave frequency
- \( h \) = amplitude
- \( \tau \) = timescale of frequency change
- \( C \) is a known numerical constant

These equations determine \( r \):
- \( f, h, \tau \) are all measurable

Redshift: determined from optical emission

- Main issue: where in the sky did the grav. wave signal come from?
  - Answer: triangulation

- Upshot: typical error of \( \epsilon \sim (6^\circ)^2 \)

With 3-4 GW detectors, source galaxy & redshift can be identified
GW170817 FACTSHEET

LIGO-Hanford | LIGO-Livingston | Virgo
---|---|---
observed by | H, L, V | inferred duration from 30 Hz to 2048 Hz** | ~ 60 s
source type | binary neutron star (NS) | inferred # of GW cycles from 30 Hz to 2048 Hz** | ~ 3000
date | 17 August 2017 | initial astronomer alert latency* | 27 min
signal-to-noise ratio | 32.4 | HLV sky map alert latency* | 5 hrs 14 min
gamma-ray, X-ray, ultraviolet, optical, infrared, radio
false alarm rate | < 1 in 80 000 years | HLV sky area1 | 28 deg2
light-years
distance | 85 to 160 million light-years | # of EM observatories that followed the trigger | ~ 70

total mass | 2.73 to 3.29 $M_\odot$ | gamma-ray, X-ray, ultraviolet, optical, infrared, radio
primary NS mass | 1.36 to 2.26 $M_\odot$ | host galaxy | NGC 4993
also observed in
secondary NS mass | 0.66 to 1.36 $M_\odot$ | source RA, Dec | 13°09'48" - 23°22'53"
radiated GW energy | > 0.25 $M_\odot$ c² | sky location | in Hydra constellation
likely ≤ 14 km
radius of a 1.4 $M_\odot$ NS | effective spin parameter | 0.01 to 0.17
(without and with host galaxy identification) | ≤ 56° and ≤ 28°
effective precession spin parameter | unconstrained
GW speed deviation from speed of light | < few parts in 10¹⁵

Images: time-frequency traces (top), HLV sky map
(left, HL = light blue, HLV = dark blue, improved HLV = green,
optical source location = cross-hair)

GW = gravitational wave, EM = electromagnetic,
$M_\odot$ = solar mass = 2x10³⁰ kg,
HLV = LIGO Hanford/Livingston, V = Virgo

Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
190% credible region

FIG. 1. Time-frequency representations [65] of data containing the gravitational-wave event GW170817, observed by the LIGO-
Hanford (top), LIGO-Livingston (middle), and Virgo (bottom)
detectors. Times are shown relative to August 17, 2017 12:41:04
UTC. The amplitude scale in each detector is normalized to the
detector’s noise amplitude spectral density. In the LIGO data,
independently observable noise sources and a glitch that occurred
in the LIGO-Livingston detector have been subtracted, as
described in the text. This noise mitigation is the same as that
used for the results presented in Sec. IV.
GW170817 was the outcome of merger of two neutron stars, each a dense remnant of a past supernova explosion, that had been orbiting each other closely.

It finally arrived with triplets: the detection of GW170817 by the LIGO and Virgo observatories, followed 1.7 seconds later by the discovery of an associated gamma-ray burst, followed 11 hours later by the discovery of an optical counterpart. GW170817 comprised two compact objects with masses in the range of 1.36–2.26 solar masses and 0.86–1.36 solar masses, consistent with a binary neutron star system.
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 km s$^{-1}$ 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.
STANDARD SIREN GW170817

- The orange bands show the range of values inferred from the SHoES analysis that combines Cepheid variable and type Ia supernovae data from the relatively nearby universe.

- The darker and lighter coloured bands indicate 68.3% and 95.4% credible intervals respectively. Note that the Planck and SHoES results are not in agreement with each other at the 95.4% probability level.

- Gravitational-wave result is, however, consistent with both the Planck and SHoES values.
Marginalized posterior density for $H_0$ (blue curve). Constraints at 1- and 2σ from Planck (Planck Collaboration et al. 2016) and SHoES (Riess et al. 2016) are shown in green and orange.

The maximum a posterior value and minimal 68.3% credible interval from this is $H_0 = 70.0^{+12.0}_{-8.0}$ km s$^{-1}$ Mpc$^{-1}$. The 68.3% (1σ) and 95.4% (2σ) minimal credible intervals are indicated by dashed and dotted lines.
Figure shows the joint constraints on $H_0$ and the inclination of the binary neutron star system and illustrates that there is a degeneracy between these quantities, meaning that the data assigns similar probabilities to certain combinations of $H_0$ and inclination.

This degeneracy arises because of the significant correlation between distance and inclination angle for a gravitational-wave source.

The gravitational-wave amplitude emitted by a distant binary viewed face-on or face-off is similar to that of a closer binary viewed edge-on.

It also causes the extended low-probability 'tail' for high values of $H_0$, since the solid blue curve in previous figure is essentially obtained by projecting along the vertical axis the contour plot in Figure 4.
STANDARD SIREN GW170817 INFEERENCE ON $H_0$ AND INCLINATION

➢ The darkest shading shows the region of highest probability. Note the significant correlation between inclination angle and inferred Hubble constant.

➢ This is because of the significant correlation between distance and inclination angle for a gravitational-wave source.

➢ The gravitational-wave amplitude emitted by a distant binary viewed face-on or face-off is similar to that of a closer binary viewed edge-on.

➢ The highest probability region corresponds to inclination angles close to 180 degrees - indicating that GW170817 was viewed almost face-off.

LIGO- VIRGO Scientific Collaboration-2017
Contour plot summarising what analysis infers jointly about the value of the Hubble constant (horizontal axis) and the inclination of the binary neutron star system’s orbital plane (vertical axis; the right-hand axis shows inclination angle in degrees and the left-hand axis shows cosine of the inclination angle).
Due to a combination of statistical measurement error from the noise in the detectors, instrumental calibration uncertainties (Abbott et al. 2017a), and a geometrical factor dependent upon the correlation of distance with inclination angle.
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 deg² 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 system.
Gravitational-wave source without an electromagnetic counterpart

**SIREN GW190814 - BEST LOCALIZED DARK SIREN**

Localize GW190814’s source to within 18.5 deg^2 at 90% probability, as shown in Figure 2. This is comparable to the localization of GW170817 (Abbott et al. 2017a, 2019a).

*Figure 1.* Time–frequency representations (Chatterji et al. 2004) of data containing GW190814, observed by LIGO Hanford (top), LIGO Livingston (middle), and Virgo (bottom). Times are shown relative to 2019 August 14, 21:10:39 UTC. Each detector’s data are whitened by their respective noise amplitude spectral density and a $Q$-transform is calculated. The colorbar displays the normalized energy reported by the $Q$-transform at each frequency. These plots are not used in our detection procedure and are for visualization purposes only.

*Figure 2.* Posterior distributions for the sky location of GW190814. The contours show the 90% credible interval for a LIGO Livingston–Virgo (blue) and LIGO Hanford–LIGO Livingston–Virgo (orange) detector network based on the rapid localization algorithm BAYESTAR (Singer & Price 2016). The sky localization circulated 13.5 hours after the event, based on a LIGO Hanford–LIGO Livingston–Virgo analysis with the LALINFERERE stochastic sampling software (Veitch et al. 2015), is shown in green. The purple contour indicates the final sky localization as presented in this paper, which constrains the source to within 18.5 deg^2 at 90% probability.
# FACT SHEET FOR GW 190814

<table>
<thead>
<tr>
<th></th>
<th>EOBNR PHM</th>
<th>Phenom PHM</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary mass $m_1/M_\odot$</td>
<td>23.2$^{+1.0}_{-0.9}$</td>
<td>23.2$^{+1.3}_{-1.1}$</td>
<td>23.2$^{+1.1}_{-1.0}$</td>
</tr>
<tr>
<td>Secondary mass $m_2/M_\odot$</td>
<td>2.59$^{+0.08}_{-0.08}$</td>
<td>2.58$^{+0.09}_{-0.10}$</td>
<td>2.59$^{+0.08}_{-0.09}$</td>
</tr>
<tr>
<td>Mass ratio $q$</td>
<td>0.112$^{+0.008}_{-0.008}$</td>
<td>0.111$^{+0.010}_{-0.010}$</td>
<td>0.112$^{+0.008}_{-0.009}$</td>
</tr>
<tr>
<td>Chirp mass $M/M_\odot$</td>
<td>6.10$^{+0.06}_{-0.05}$</td>
<td>6.08$^{+0.06}_{-0.05}$</td>
<td>6.09$^{+0.06}_{-0.05}$</td>
</tr>
<tr>
<td>Total mass $M/M_\odot$</td>
<td>25.8$^{+0.9}_{-1.0}$</td>
<td>25.8$^{+1.2}_{-1.0}$</td>
<td>25.8$^{+1.0}_{-0.9}$</td>
</tr>
<tr>
<td>Final mass $M_f/M_\odot$</td>
<td>25.6$^{+1.0}_{-0.8}$</td>
<td>25.5$^{+1.2}_{-1.0}$</td>
<td>25.6$^{+0.9}_{-0.9}$</td>
</tr>
<tr>
<td>Upper bound on primary spin magnitude $\chi_1$</td>
<td>0.06</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>Effective inspiral spin parameter $\chi_{\text{eff}}$</td>
<td>0.001$^{+0.059}_{-0.056}$</td>
<td>-0.005$^{+0.061}_{-0.065}$</td>
<td>-0.002$^{+0.060}_{-0.061}$</td>
</tr>
<tr>
<td>Upper bound on effective precession parameter $\chi_p$</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Final spin $\chi_f$</td>
<td>0.28$^{+0.02}_{-0.02}$</td>
<td>0.28$^{+0.02}_{-0.03}$</td>
<td>0.28$^{+0.02}_{-0.02}$</td>
</tr>
<tr>
<td>Luminosity distance $D_L$/Mpc</td>
<td>235$^{+40}_{-44}$</td>
<td>249$^{+39}_{-43}$</td>
<td>241$^{+41}_{-45}$</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>0.051$^{+0.008}_{-0.009}$</td>
<td>0.054$^{+0.008}_{-0.009}$</td>
<td>0.053$^{+0.009}_{-0.010}$</td>
</tr>
<tr>
<td>Inclination angle $\Theta$/rad</td>
<td>0.9$^{+0.3}_{-0.2}$</td>
<td>0.8$^{+0.2}_{-0.2}$</td>
<td>0.8$^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td>Signal to noise ratio in LIGO Hanford $\rho_H$</td>
<td>10.6$^{+0.1}_{-0.2}$</td>
<td>10.7$^{+0.0}_{-0.2}$</td>
<td>10.7$^{+0.1}_{-0.2}$</td>
</tr>
<tr>
<td>Signal to noise ratio in LIGO Livingston $\rho_L$</td>
<td>22.21$^{+0.09}_{-0.15}$</td>
<td>22.16$^{+0.09}_{-0.17}$</td>
<td>22.18$^{+0.10}_{-0.17}$</td>
</tr>
<tr>
<td>Signal to noise ratio in Virgo $\rho_V$</td>
<td>4.3$^{+0.5}_{-0.5}$</td>
<td>4.1$^{+0.2}_{-0.6}$</td>
<td>4.2$^{+0.2}_{-0.6}$</td>
</tr>
<tr>
<td>Network Signal to noise ratio $\rho_{\text{HLV}}$</td>
<td>25.0$^{+0.1}_{-0.2}$</td>
<td>24.9$^{+0.1}_{-0.2}$</td>
<td>25.0$^{+0.1}_{-0.2}$</td>
</tr>
</tbody>
</table>

Table 1. Source properties of GW190814: We report the median values along with the symmetric 90% credible intervals for the SBOBNRv4PHM (EOBNR PHM) and IMRPhenomPV3HM (Phenom PHM) waveform models. The primary spin magnitude and the effective precession is given as the 90% upper limit. The inclination angle is folded to $[0, \pi/2]$. The last column is the result of combining the posteriors of each model with equal weight. The sky location of GW190814 is shown in Figure 2.
SIREN GW190814- BEST LOCALIZED DARK SIREN

- It is a good candidate for the statistical cross-correlation method.
- 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 $H_0 \in [20, 140] \text{ km s}^{-1} \text{ Mpc}^{-1}$ 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 $H_0 = 75^{+59}_{-13} \text{ km s}^{-1} \text{ Mpc}^{-1}$ using GW190814 alone (mode and 68.3% highest posterior density interval; the median and 90% symmetric credible interval is $H_0= 83^{+55}_{-53} \text{ km s}^{-1} \text{ Mpc}^{-1}$), which can be compared to $H_0 = 75^{+40}_{-32} \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Soares-Santos et al. 2019) obtained using the dark siren GW170814 alone.
## GW170814: FACTSHEET

<table>
<thead>
<tr>
<th>Observed by</th>
<th>H1, L1, V1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source type</td>
<td>Black hole (BH) binary</td>
</tr>
<tr>
<td>Date</td>
<td>14 Aug 2017</td>
</tr>
<tr>
<td>Time</td>
<td>10:30:43 UTC</td>
</tr>
<tr>
<td>Online trigger latency</td>
<td>~ 30 s</td>
</tr>
<tr>
<td>Signal arrival time delay</td>
<td>~ 1.8 ms before H1 and 14 ms before V1</td>
</tr>
<tr>
<td>Signal-to-noise ratio</td>
<td>18</td>
</tr>
<tr>
<td>False alarm rate</td>
<td>~ 1 in 27,000 years</td>
</tr>
<tr>
<td>Probability of noise producing V1 SNR peak</td>
<td>0.3%</td>
</tr>
<tr>
<td>Distance</td>
<td>1.1 to 2.2 billion light-years</td>
</tr>
<tr>
<td>Redshift</td>
<td>0.07 to 0.14</td>
</tr>
<tr>
<td>Total mass</td>
<td>53 to 59 M☉</td>
</tr>
<tr>
<td>Primary BH mass</td>
<td>28 to 36 M☉</td>
</tr>
<tr>
<td>Secondary BH mass</td>
<td>21 to 28 M☉</td>
</tr>
<tr>
<td>Mass ratio</td>
<td>0.6 to 1.0</td>
</tr>
<tr>
<td>Remnant BH mass</td>
<td>51 to 56 M☉</td>
</tr>
<tr>
<td>Remnant BH spin</td>
<td>0.65 to 0.77</td>
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<tr>
<td>Duration from 30 Hz</td>
<td>~ 0.26 to 0.28 s</td>
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<tr>
<td># of cycles from 30 Hz</td>
<td>~ 15 to 16</td>
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<tr>
<td>Credible region sky area (with V1)</td>
<td>~ 60 deg²</td>
</tr>
<tr>
<td>Credible region sky area (without V1)</td>
<td>~ 1160 deg²</td>
</tr>
<tr>
<td>Latitude, longitude</td>
<td>45° S, 73° W</td>
</tr>
<tr>
<td>Sky location</td>
<td>In direction of Eridanus constellation</td>
</tr>
<tr>
<td>RA, Dec</td>
<td>03°11', -44°57'</td>
</tr>
<tr>
<td>Peak GW strain (10-22)</td>
<td>~ 6, 6, 5</td>
</tr>
<tr>
<td>Peak stretching of interferometer arm</td>
<td>~ 1.2, 1.2, 0.8 mm</td>
</tr>
<tr>
<td>Frequency at peak</td>
<td>155 to 203 Hz</td>
</tr>
<tr>
<td>GW strain</td>
<td>1480 to 1930 km</td>
</tr>
<tr>
<td>Peak GW luminosity</td>
<td>3.2 to 4.2 x 10⁶⁴ erg s⁻¹</td>
</tr>
<tr>
<td>Radiated GW energy</td>
<td>2.4 to 3.1 M☉c²</td>
</tr>
</tbody>
</table>
STANDARD SIREN GW170814

GW170814 as a standard siren, combined with a photometric redshift catalog from the Dark Energy Survey (DES)

➢ The luminosity distance is obtained from the gravitational wave signal detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO)/Virgo Collaboration (LVC) on 2017 August 14.

➢ The redshift information is provided by the DES Year 3 data. Black hole mergers such as GW170814 are expected to lack bright electromagnetic emission to uniquely identify their host galaxies and build an object-by-object Hubble diagram.

➢ However, they are suitable for a statistical measurement, provided that a galaxy catalog of adequate depth and redshift completion is available.
Hubble constant posterior distribution obtained by marginalizing over \( \sim 77,000 \) possible host galaxies (red line), showing the maximum value (solid vertical line). The maximum a posteriori and its 68% confidence level is \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (-32, +40) for a flat prior in the range [20,140] km s \(^{-1}\) Mpc \(^{-1}\). The shaded region represents the change in the posterior when different fractions of the localization volume are considered (from 90% to 99.7% of the LIGO/Virgo luminosity distance posterior). The PDF computed from the larger volume has been renormalized to have the same value of the 90% localization volume \( H_0 \) posterior at the maximum, to highlight differences below and beyond the main peak. The posterior obtained by Abbott et al. (2017a) for the bright standard siren event GW170817, associated to one galaxy, is shown in gray. The prior used in that work was flat-in-log over a narrower range ([50,140] km s \(^{-1}\) Mpc \(^{-1}\)), and the posterior has been rescaled by a factor 0.2 for visualization purposes. The 68% CL of both PDFs is shown by the dashed lines. Constraints from Planck (Planck Collaboration et al. 2018) and Supernovae and \( H_0 \) for the Equation of State (SHoES; Riess et al. 2016, 2018) at 1σ are shown in purple boxes.
STANDARD SIREN GW170814

GW170814 as a standard siren, combined with a photometric redshift catalog from the Dark Energy Survey (DES)

- The first Hubble parameter measurement using a black hole merger.
- The analysis results in $H_o = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (-32, +40), which is consistent with both SN Ia and cosmic microwave background measurements of the Hubble constant.
- The quoted 68% credible region comprises 60% of the uniform prior range $[20, 140] \text{ km s}^{-1} \text{ Mpc}^{-1}$, and it depends on the assumed prior range.
- If we take a broader prior of $[10, 220] \text{ km s}^{-1} \text{ Mpc}^{-1}$, we find $H_o = 78 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (-24, +96) (57% of the prior range).
- Although a weak constraint on the Hubble constant from a single event is expected using the dark siren method, a multifold increase in the LVC event rate is anticipated in the coming years and combinations of many sirens will lead to improved constraints on $H_0$. 
Additional GW detections by LIGO and Virgo can be expected to constrain the Hubble constant to a precision of approximately two per cent within five years and approximately one per cent within a decade.

This is because observing gravitational waves from the merger of two neutron stars, together with the identification of a host galaxy, enables a direct measurement of the Hubble constant independent of the systematics associated with other available methods.

In addition to clarifying the discrepancy between existing low-redshift (local ladder) and high-redshift (cosmic microwave background) measurements, a precision measurement of the Hubble constant is of crucial value in elucidating the nature of dark energy.

We find that, if it is possible to independently measure a unique.
CONCLUSIONS AND FUTURE PROSPECTS

1) GW Standard Sirens can now provide the most significant cosmological parameters

2) In the future, we will have more low-redshift standard 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 $13\%/N$.

3) In 2023, about 50 events will be observed 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.

4) The Dark Sirens are highly useful in measuring the cosmological parameters without any EM counterparts.

5) Additional standard-siren measurements from future gravitational-wave sources will provide precision constraints of this important cosmological parameter.
THANKS

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Standard Siren and Dark Siren

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