Gravitational-Wave Standard Sirens

A New Window on the Hubble Tension

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Talk Outline

- **The Hubble Tension**
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- **Outlook and Conclusions**
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The Hubble Tension

The Cosmological Crisis

Early vs. Late Universe Measurements

- **Early Universe Probes**:
  - Calibrated via Cosmic Microwave Background (CMB) anisotropies.
  - Planck Collaboration yields $H_0 = 67.4 \pm 0.5$ km s^{-1}Mpc^{-1} under flat ΛCDM.
- **Late Universe Probes**:
  - Calibrated via the local distance ladder (Cepheids + Type Ia Supernovae).
  - SH0ES Collaboration yields $H_0 = 73.0 \pm 1.0$ km s^{-1}Mpc^{-1}.

The Tension

The disagreement between early and late universe measurements stands at a statistical significance of $\sim 5\sigma$. This suggests either unrecognized systematic errors or new physics beyond ΛCDM.

Standard Sirens as Distance Indicators

Luminosity Distance in GW Astronomy

Direct Calibration Without the Distance Ladder

Compact binary coalescences act as **standard sirens** because the gravitational-wave (GW) signal carries direct information about the absolute luminosity distance d_L.

The primary GW strain amplitude $h(t)$ for a merging binary is given by:

$$h(t) \propto \frac{\mathcal{M}_c^{5/3} f(t)^{2/3}}{d_L} \tag{1}$$

where $\mathcal{M}_c$ is the chirp mass and $f(t)$ is the gravitational-wave frequency.

By measuring the frequency evolution (which determines $\mathcal{M}_c$), the absolute distance d_L is obtained directly:

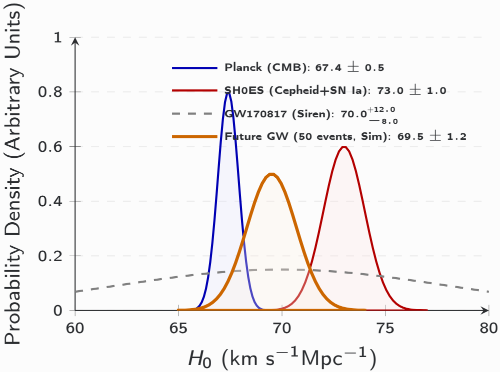
$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} \tag{2}$$

Resolving the Tension

H0 Constraints & Resolving the Tension

Comparing Current Measurements and Future Projections

- **GW170817**:
  - The first binary neutron star merger.
  - Yielded an independent, direct measurement of $H_0 \approx 70^{+12}_{-8}$ km s^{-1}Mpc^{-1}.
- **Future Forecasts**:
  - A sample of ~ 50 bright standard sirens will constrain H_0 to $\sim 1.5\%$.
  - This precision is sufficient to arbitrate the Hubble tension.



Comparison of Cosmological Probes

Summary of Current H0 Measurements

Table: Key measurements of the Hubble constant H_0 across different methods.

Method	**Probe / Catalog**	H_0 **Value (km s^{-1}Mpc^{-1})**	**Reference**
Early Universe	Planck CMB	67.4 ± 0.5	Planck Collab. (2020)
Local Ladder	SH0ES (Cepheids)	73.0 ± 1.0	Riess et al. (2022)
TRGB	CCHP (TRGB)	69.8 ± 0.8	Freedman et al. (2021)
Strong Lensing	H0LiCOW	$73.3^{+1.7}_{-1.8}$	Wong et al. (2020)
Standard Sirens	**GW170817 (Siren)**	$70.0^{+12.0}_{-8.0}$	**Abbott et al. (2017)**

Note: Standard sirens represent the only probe capable of a direct, self-calibrated distance measurement at cosmological distances without the need for a local distance ladder.

Conclusions & Takeaways

- **The Hubble Tension remains robust** at $\sim 5\sigma$ between CMB measurements (67.4 ± 0.5) and local distance ladder measurements (73.0 ± 1.0).
- **Standard Sirens offer a clean, independent path** to arbitrate this tension, relying on general relativity for absolute distance calibration.
- **A single event (GW170817) demonstrated the proof of concept**, establishing $H_0 \approx 70^{+12}_{-8}$ km s^{-1}Mpc^{-1}.
- **Next-generation catalogs (LVK O4/O5) will provide** ~ 50 **events**, yielding a 1.5% measurement of H_0, which will decisively test cosmological models.

Thank You

Questions & Comments

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