
Gravitational-Wave Standard Sirens

A New Window on the Hubble Tension

Dr. Elena Vance

Institute for Gravitational Physics, Department of Astrophysics

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Talk Outline

- **The Hubble Tension**
 - Early vs. Late Universe probes
 - Systematics vs. New Physics
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 - Gravitational-wave distance calibration
 - Absolute vs. relative measurements
- **H0 Constraints & PGFPlots**
 - Analysis of GW170817
 - Forecasts for future catalogs
- **Outlook and Conclusions**
 - Combining EM and GW data
 - Key takeaways

The Hubble Tension

The Cosmological Crisis

Early vs. Late Universe Measurements

- **Early Universe Probes:**

- Calibrated via Cosmic Microwave Background (CMB) anisotropies.
- Planck Collaboration yields $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{Mpc}^{-1}$ under flat Λ CDM.

- **Late Universe Probes:**

- Calibrated via the local distance ladder (Cepheids + Type Ia Supernovae).
- SH0ES Collaboration yields $H_0 = 73.0 \pm 1.0 \text{ km s}^{-1} \text{Mpc}^{-1}$.

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 Λ CDM.

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:

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

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:

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

Resolving the Tension

H_0 Constraints & Resolving the Tension

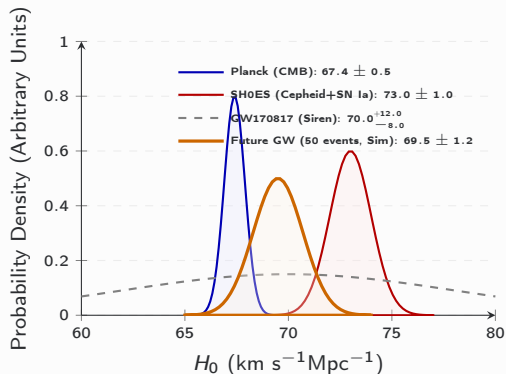
Comparing Current Measurements and Future Projections

- **GW170817:**

- The first binary neutron star merger.
- Yielded an independent, direct measurement of $H_0 \approx 70_{-8}^{+12} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

- **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 ($\text{km s}^{-1}\text{Mpc}^{-1}$)	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 $H_0 \approx 70^{+12}_{-8} \text{ km s}^{-1} \text{ Mpc}^{-1}$.
- **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

Email: elena.vance@igp.edu | Web: igp.edu/evance