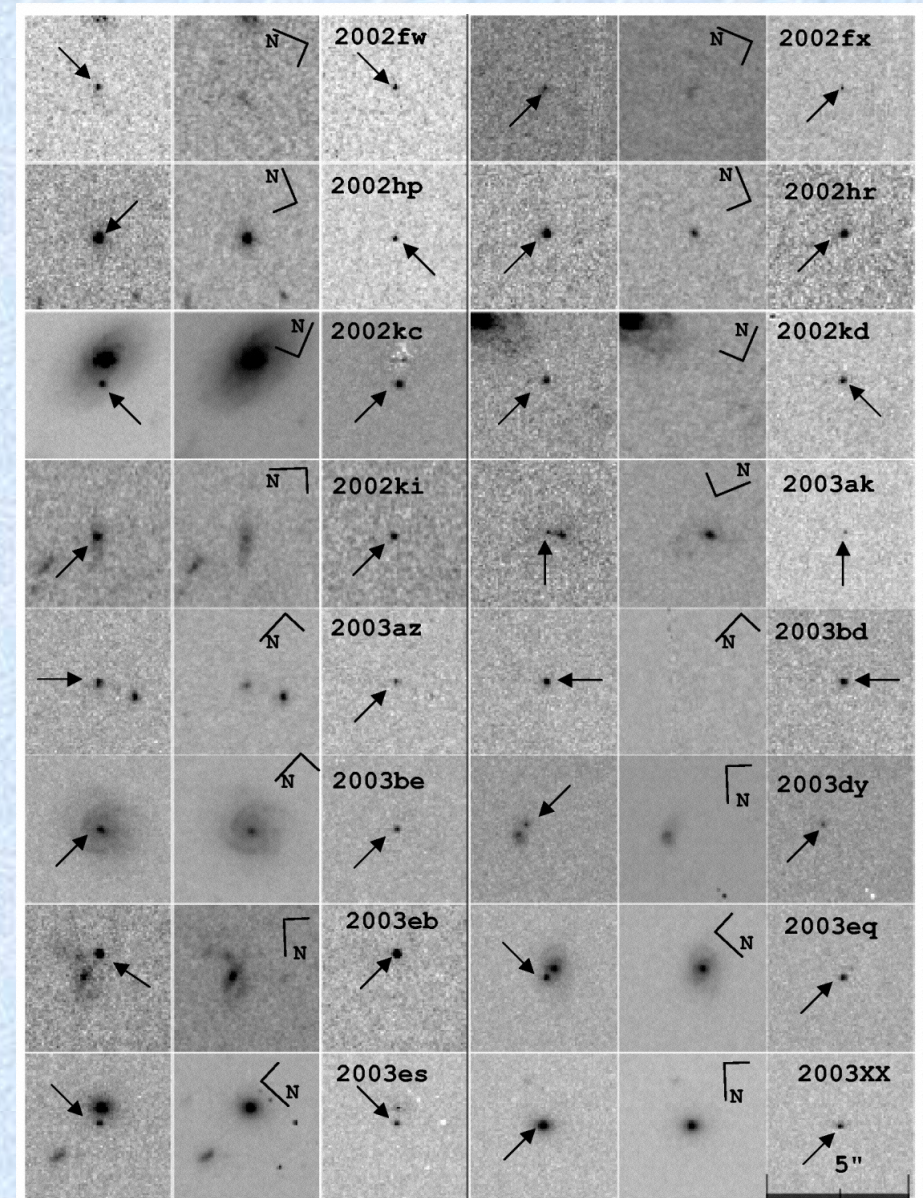


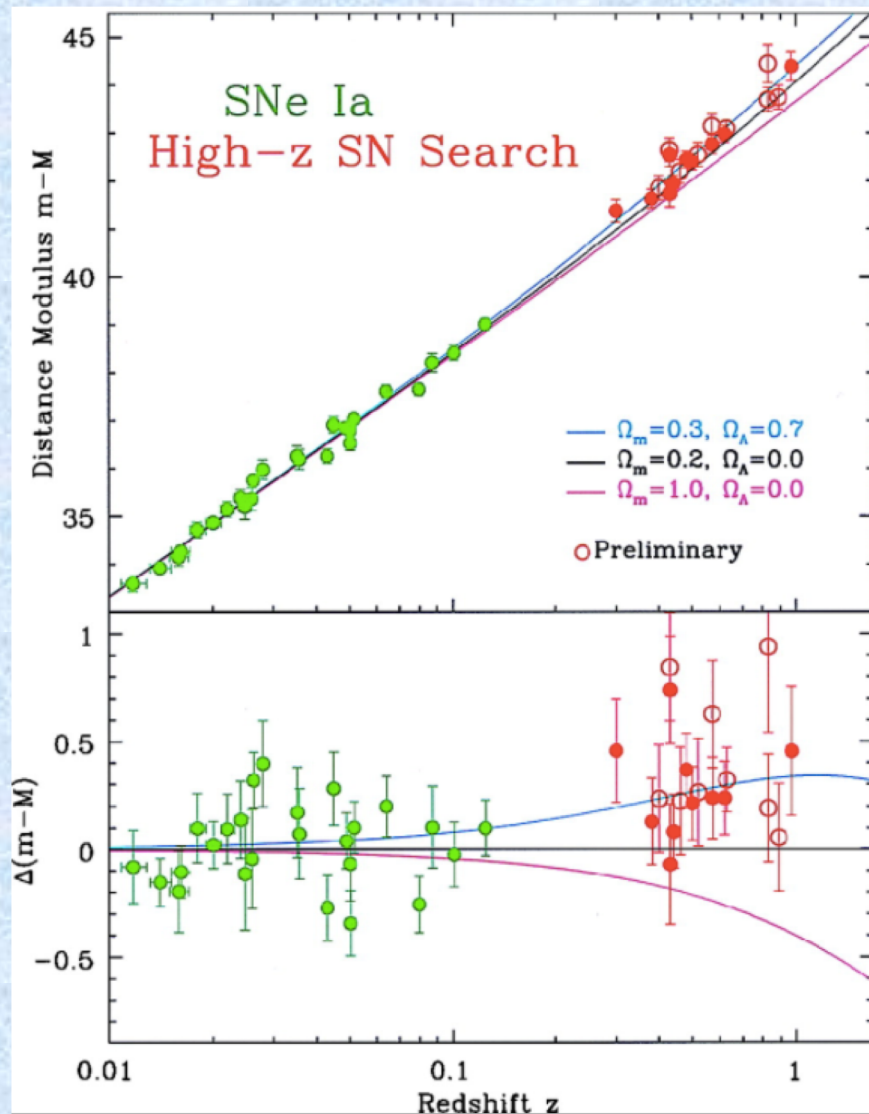
Measuring Cosmological Parameters: I. Standard Candles

- Pick standard candles, record flux, compute d_L
- Supernova of spectral type Type Ia are thermonuclear explosions of a 1.4 Msun white dwarf
- $L = 4 \times 10^9 L_{\text{sun}}$ typically, and the decay timescale of the light curve gives the exact luminosity
- $d_L \sim cH_0^{-1} z (1 + 0.5 (1 - q_0) z)$



Sn Ia results

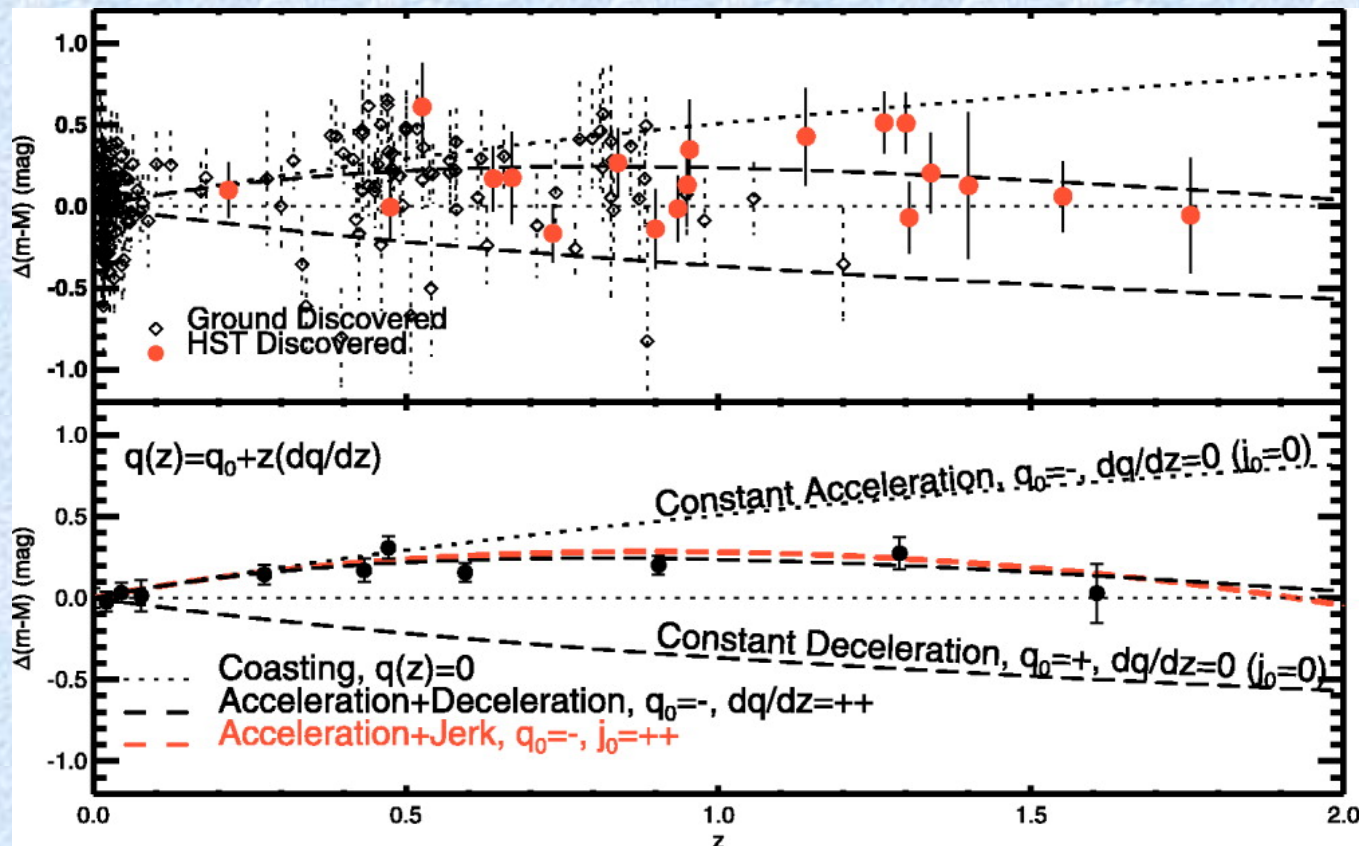
- Supernovae at $z \sim 0.5$ appear fainter than they would in the absence of acceleration.
 - Are there other factors that might make supernova appear dimmer?
 - How can we tell if cosmic acceleration is the cause?



- $m=2.5\log(f_\lambda/f_{\lambda,0})$
- Absolute magnitude M is magnitude the object would have at a distance of 10 pc
- Define the **distance modulus**
 $m-M=5\log(d_L/1\text{Mpc}) - 25$

Measuring Cosmological Parameters with Standard Candles

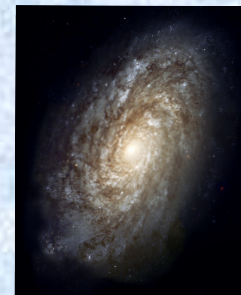
- What about interstellar dust?
- Are Type Ia SNe really standard candles?
 - The universe evolves, so maybe the progenitors evolve as well...



Riess et al. 2004

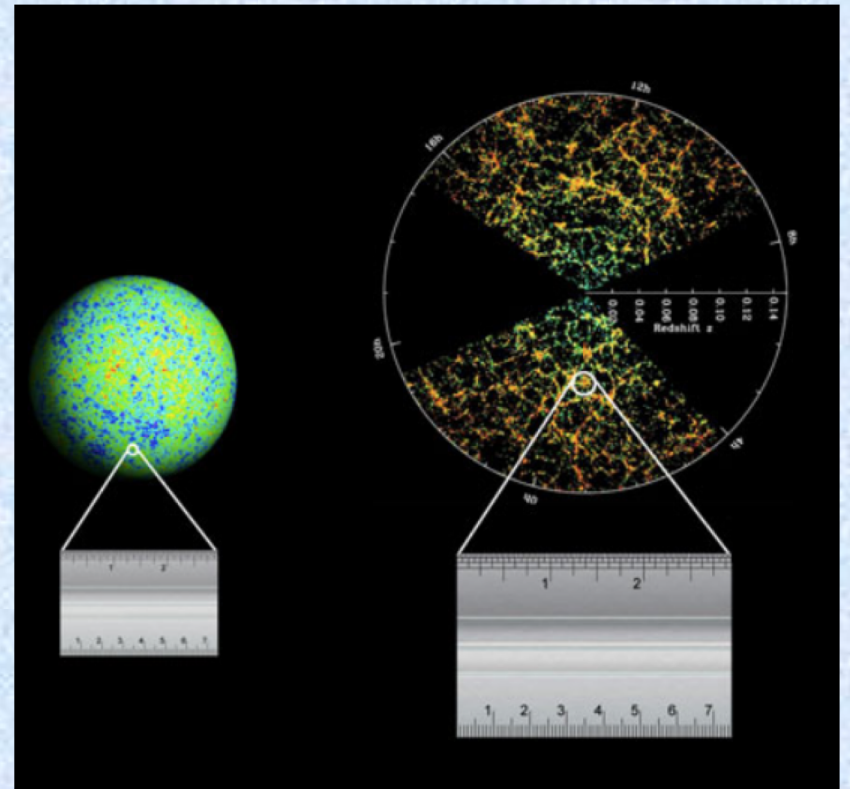
Measuring Cosmological Parameters. II. Standard Rulers

- We can use measurements of d_A to obtain the value of H_0 and q_0 .
- $d_A \sim cH_0^{-1} z (1 - 0.5(3+q_0)z)$
- How easy is this in practice?
- Do galaxies make good standard rulers?
 - If yes, then which galaxies?
 - If not, then what can we use?

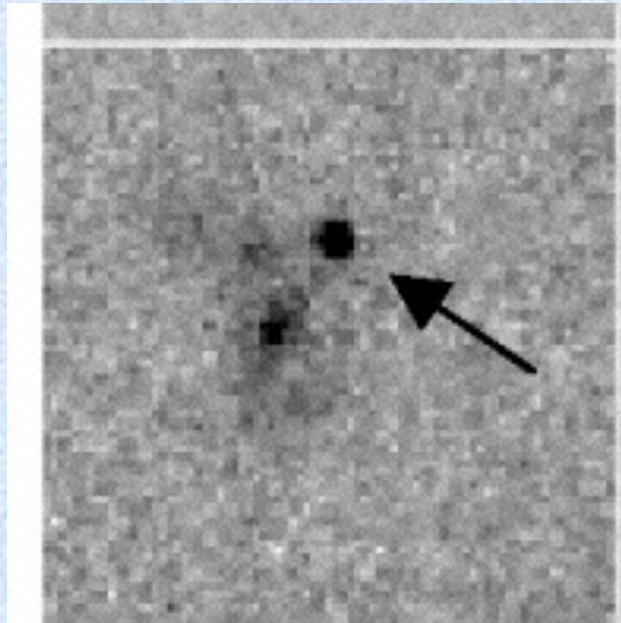


Measuring Cosmological Parameters. II. Standard Rulers

- Sound waves in the baryon-photon fluid near the time of last scattering imprint a characteristic length scale on the CMB radiation.
- This same length scale is imprinted on the large-scale structure of the universe today.
- The cosmic microwave background anisotropy, which has its origins in quantum fluctuations, also has a characteristic length scale.



Quiz #9



This image shows a newly discovered Type Ia supernova.

- You measure a flux at maximum brightness of $F = 10.3e-14$ ergs/s/cm², which is equivalent to $10.3e-17$ Watts/m².
- Later, you obtain a spectrum of the host galaxy and measure a redshift of 0.2000.

Assume Type Ia supernova are standard candles with bolometric luminosity $L = 1e43$ ergs/s, which is $1e36$ Watts.

- 1) What is the luminosity distance to this galaxy?
[Give your answer in Mpc.]
- 2) Estimate the value of Hubble's constant.
[Give answer in km/s/Mpc.]

Controversy Over the Hubble Constant!

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration*, The IM2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

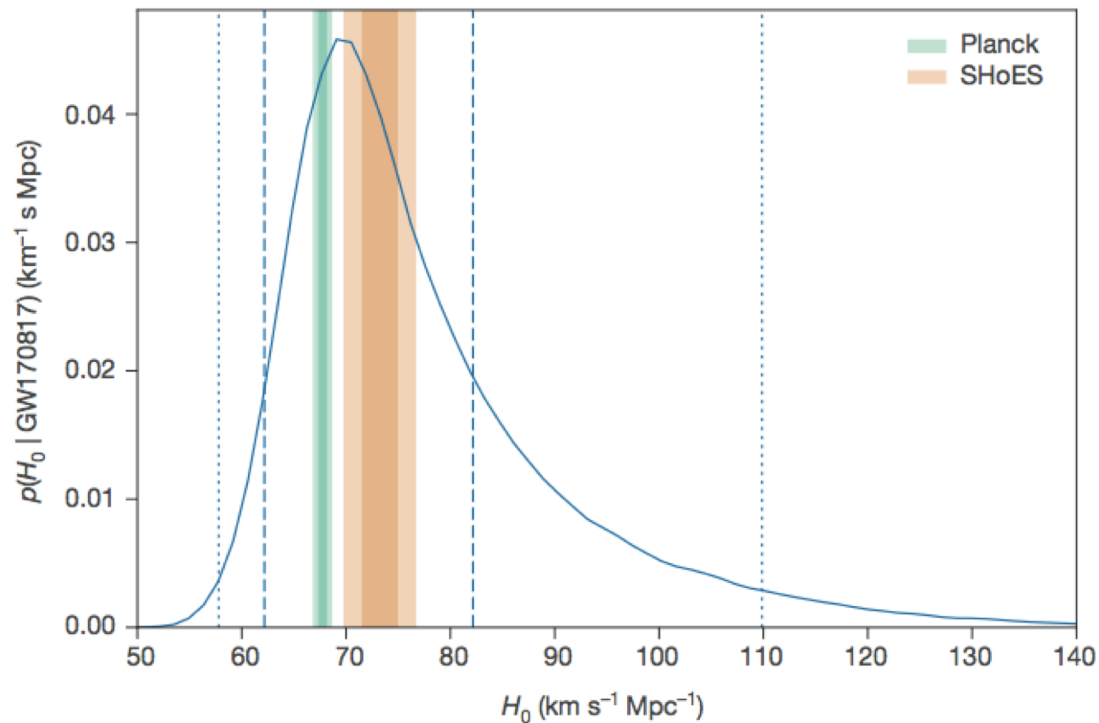


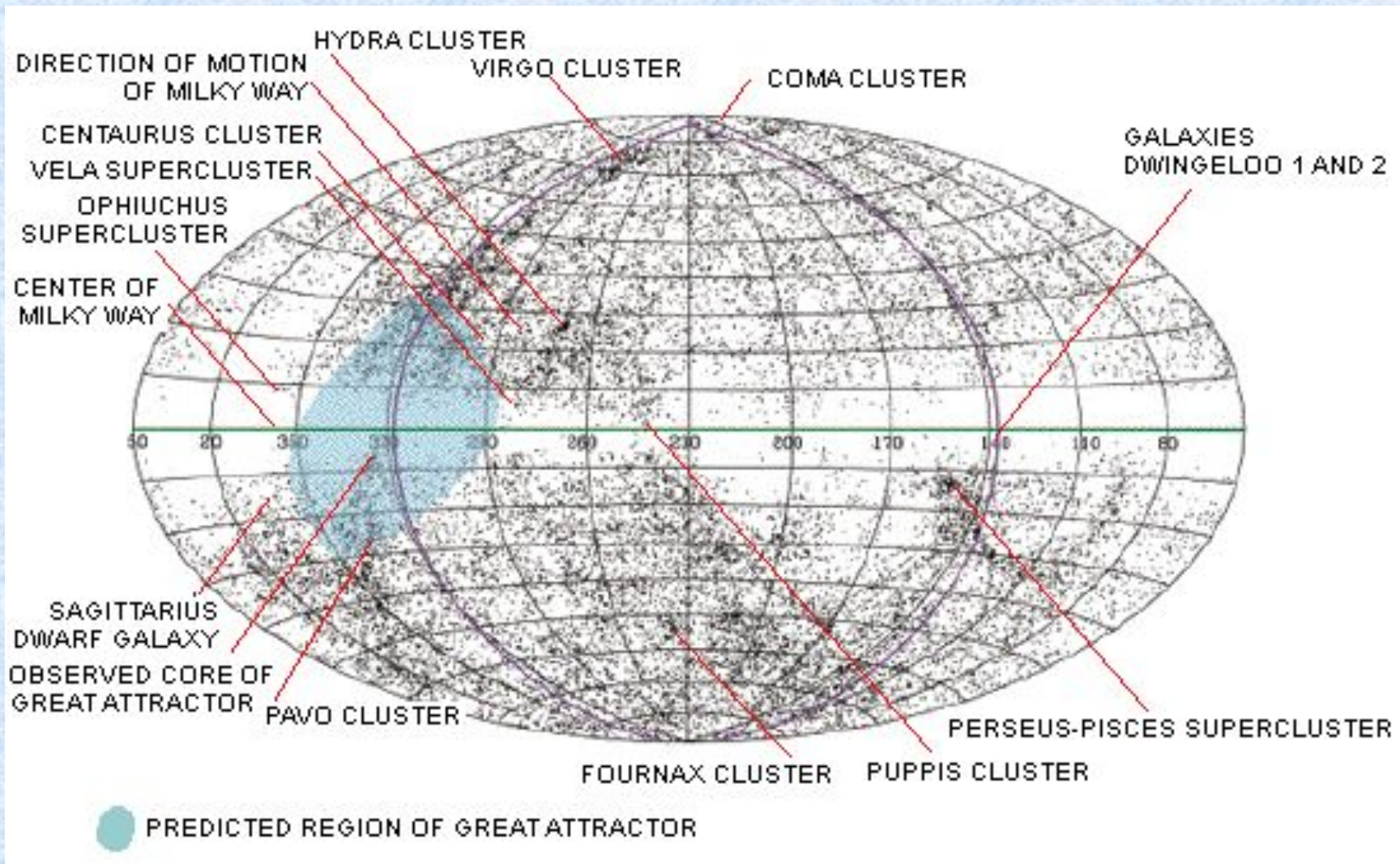
Figure 1 | GW170817 measurement of H_0 . The marginalized posterior density for H_0 , $p(H_0 | \text{GW170817})$, is shown by the blue curve. Constraints at 1σ (darker shading) and 2σ (lighter shading) from Planck²⁰ and SHoES²¹ are shown in green and orange, respectively. The maximum a posteriori value and minimal 68.3% credible interval from this posterior density function is $H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{Mpc}^{-1}$. The 68.3% (1σ) and 95.4% (2σ) minimal credible intervals are indicated by dashed and dotted lines, respectively.

The Hubble Constant

- For small z :
 - $zc = v = H_0 d$
 - What d ?
- Easy?
 - Measure z (or v)
 - Measure d
- **Problems:**
 - Peculiar velocities
 - How to measure d ?



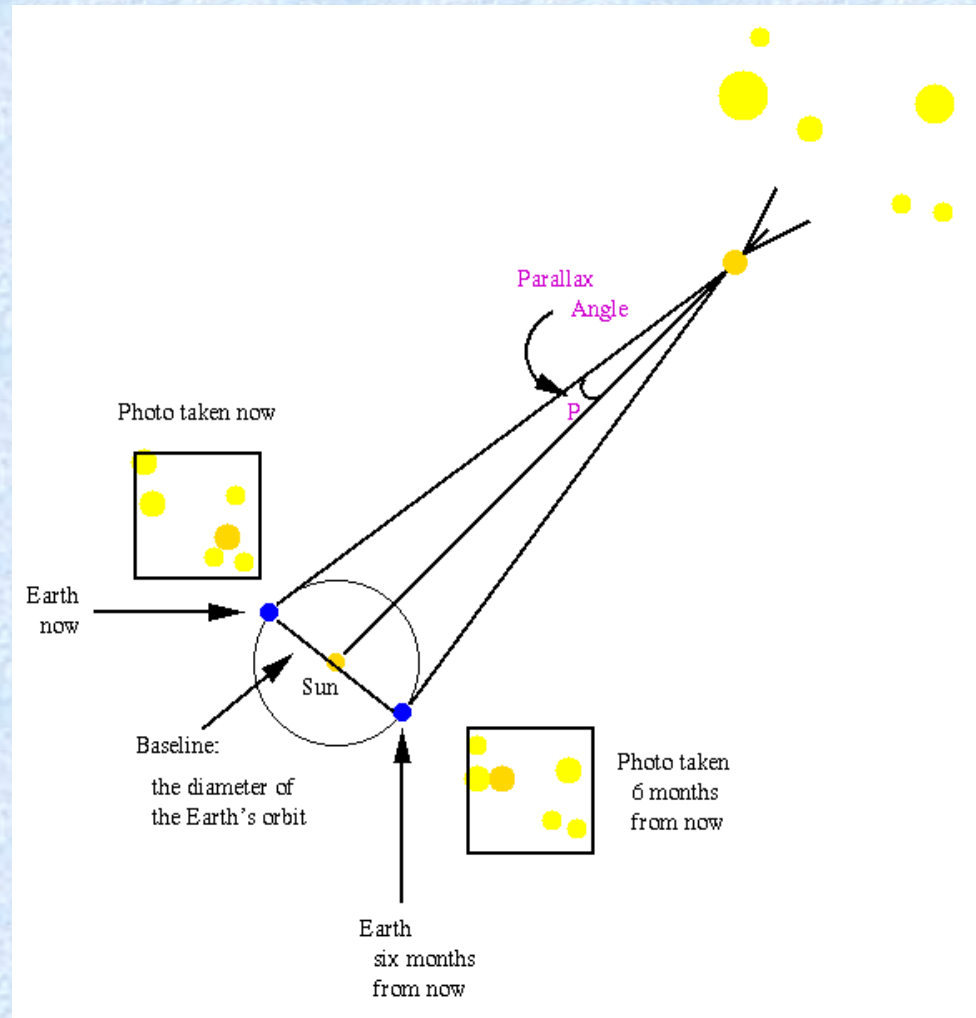
The Hubble Constant. Peculiar Velocities



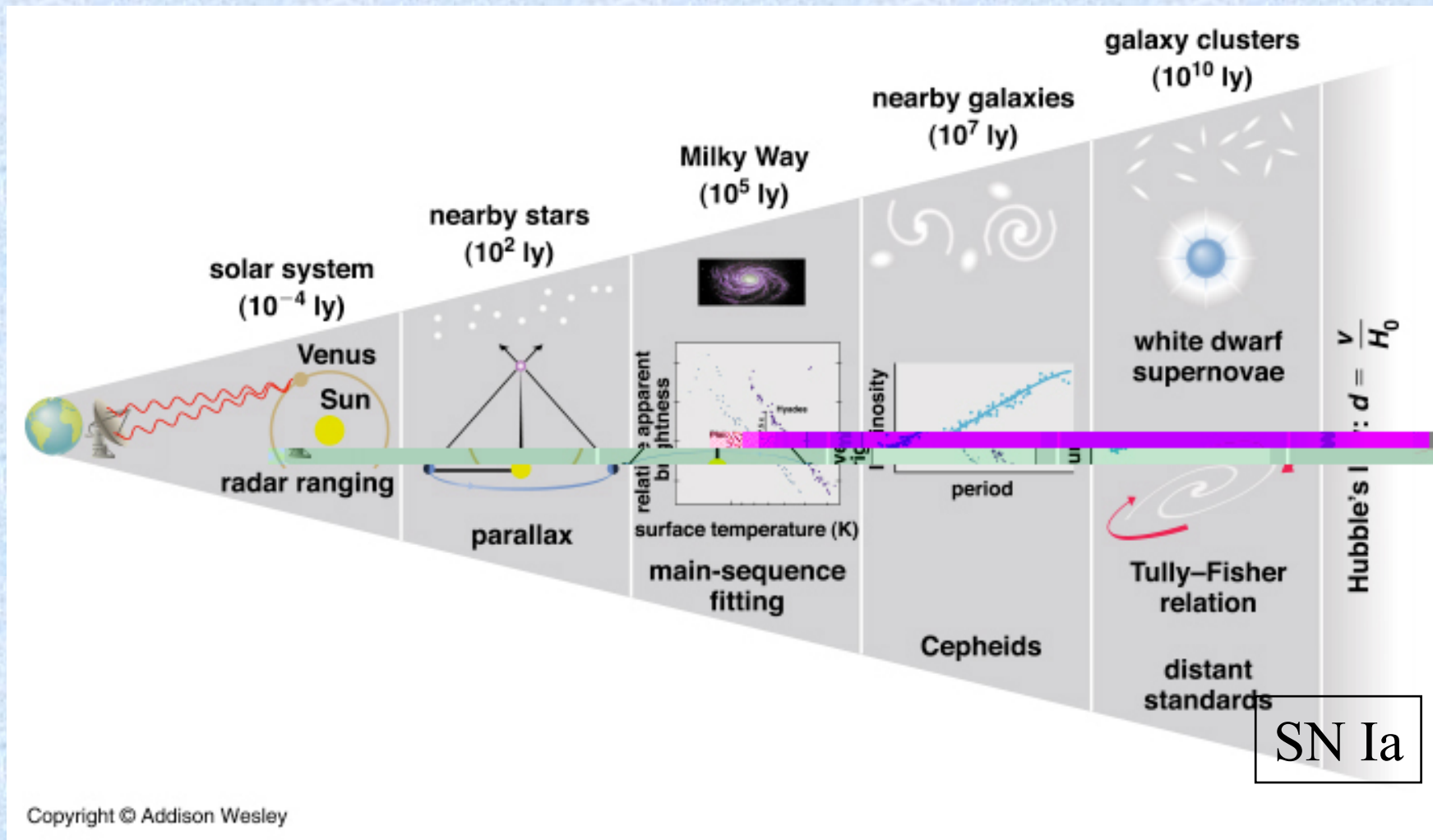
- $V = zc + v_p$, where $v_p \sim 500$ km/s
- $zc = H_0 d = H_0(100 \text{ Mpc}) = 7000$ km/s (Pure Hubble Flow)

The Hubble Constant. Measuring D

- Parallax works to \sim few 100 pc
 - Calibrate a few pulsational variables including a couple Cepheid variables



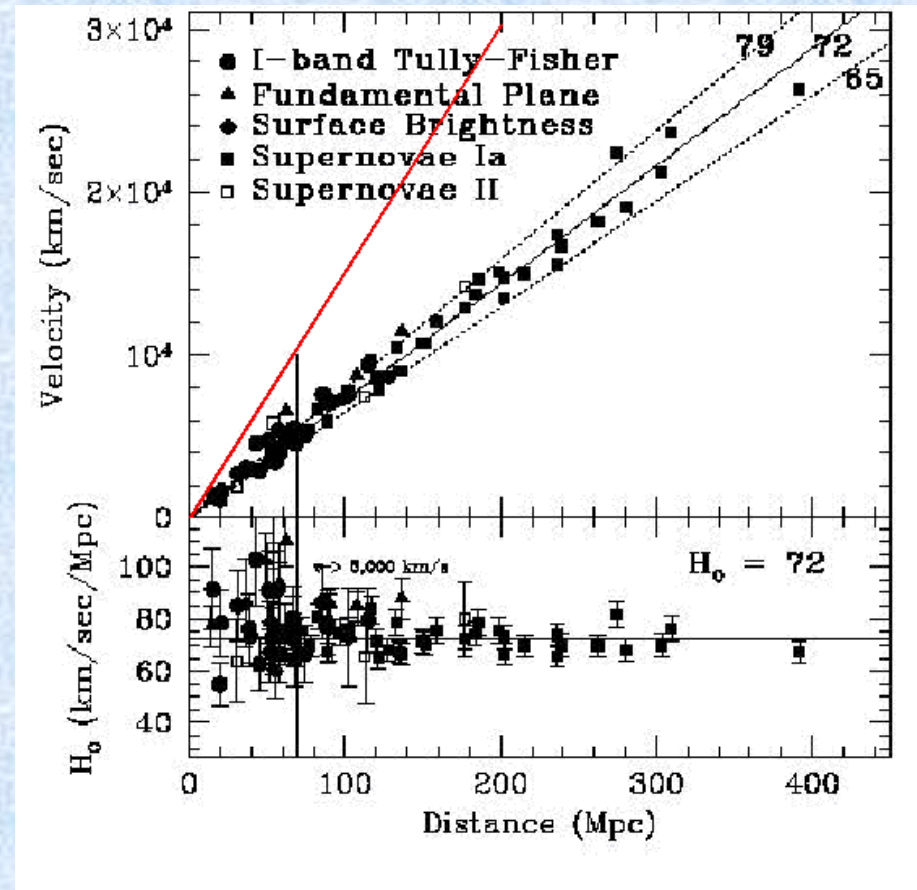
The cosmic distance ladder



The Hubble constant.

Key project strategy

- “Secondary” distance indicators calibrated with cepheids P-L relation reach into the Hubble Flow
- Cepheids P-L relation is calibrated using Cepheids in the Large Magellanic Cloud
- Can only reach $d \sim 20$ Mpc. Make corrections for Virgo Cluster infall ~ 250 km/s.



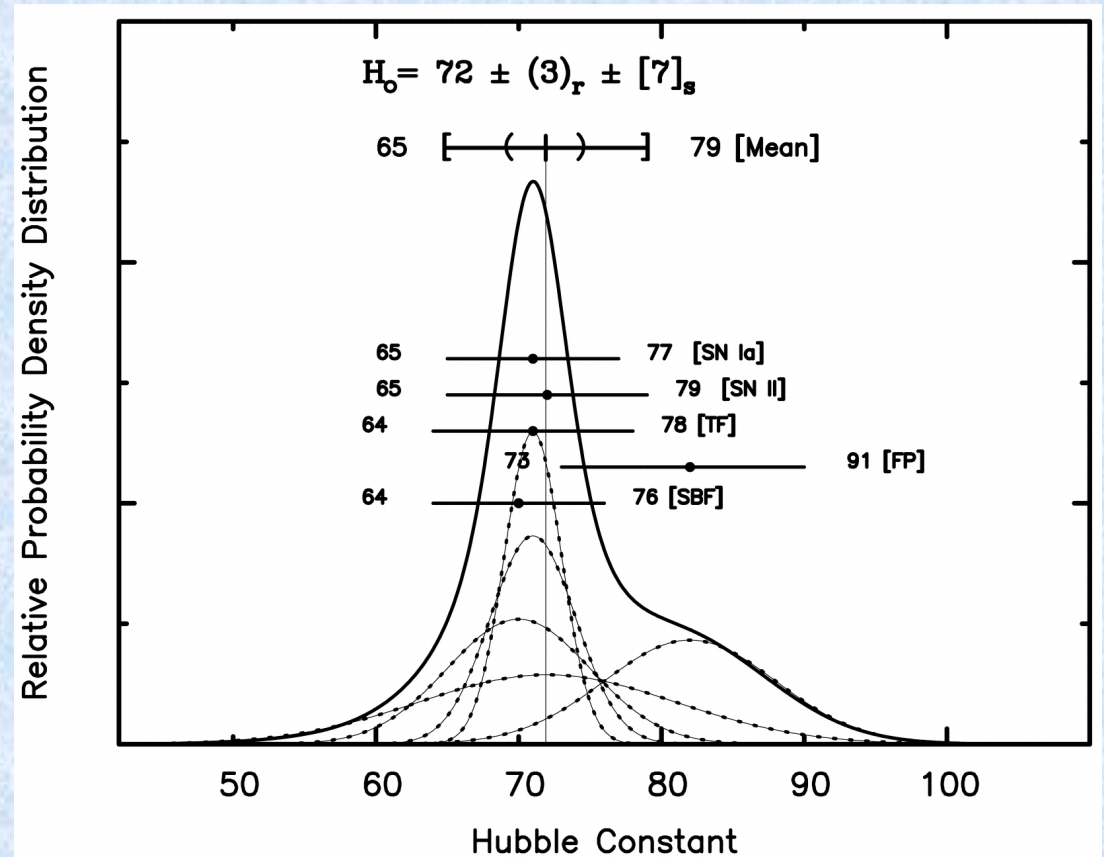
The Hubble constant.

HST Key project results

Possible Problems:

- Distance to the LMC
- Calibration of the Cepheid P-L relation (chemical composition)

What about the other parameters? Need to go to higher z .



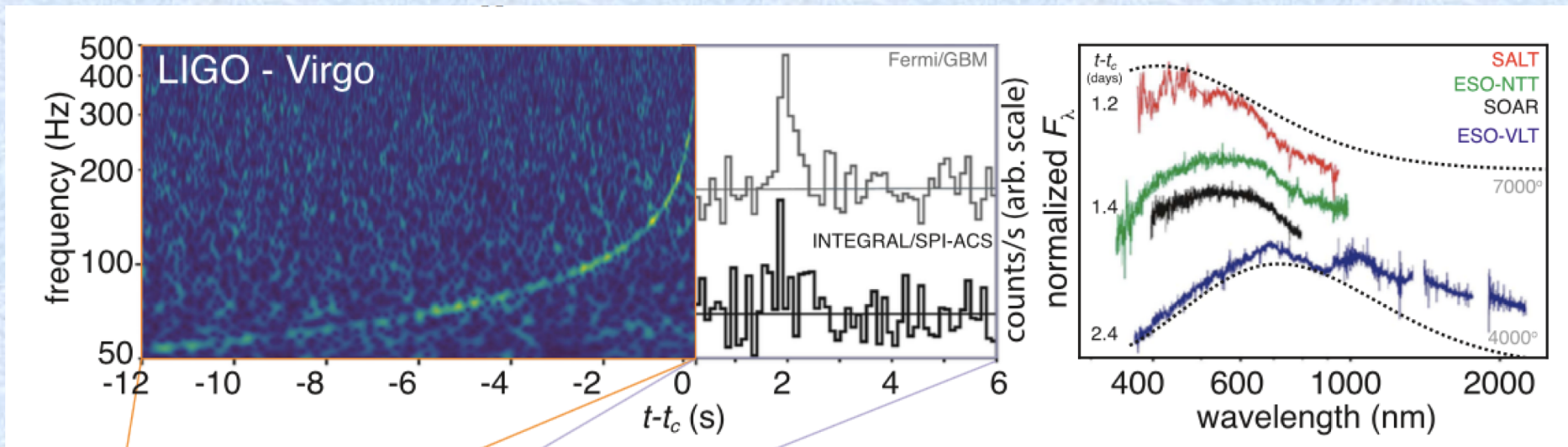
Freedman et al. 2001

Commonly accepted, but not undisputed (e.g. Sandage et al. 2006 62_{-1}^{+5})

Standard Sirens (EM & GW)

- Neutron star – neutron star mergers do not give a standard candle, but the luminosity can be worked out from the characteristic chirp of the gravitational waveform, which is determined by how rapidly the 2 stars spiral together.

Observations of a Binary NS Merger



Standard Sirens (EM & GW)

- The tricky part is to get the redshift. There's not enough structure in the gravitational waves to measure redshift.
- That's why it is such a big deal to detect the host galaxy of the NS-NS merger. The galaxy redshift can be easily measured spectroscopically.

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

Abbott et al.

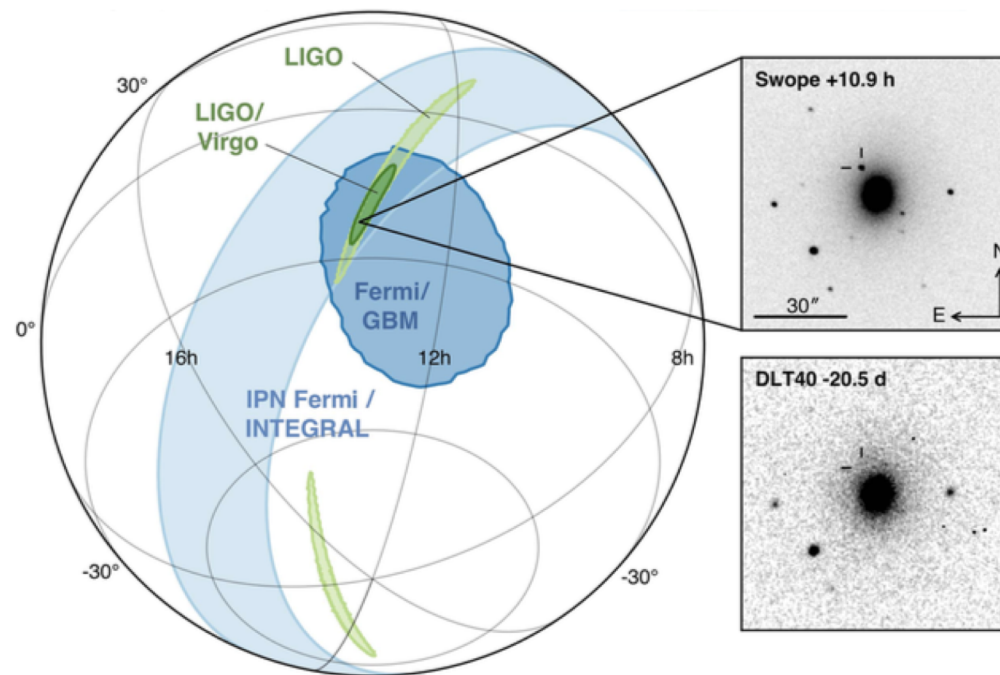


Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg²; light green), the initial LIGO-Virgo localization (31 deg²; dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi*-GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hr after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration*, The IM2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

On 17 August 2017, the Advanced LIGO¹ and Virgo² detectors observed the gravitational-wave event GW170817—a strong signal from the merger of a binary neutron-star system³. Less than two seconds after the merger, a γ -ray burst (GRB 170817A) was detected within a region of the sky consistent with the LIGO–Virgo-derived location of the gravitational-wave source^{4–6}. This sky region was subsequently observed by optical astronomy facilities⁷, resulting in the identification^{8–13} of an optical transient signal within about ten arcseconds of the galaxy NGC 4993. This detection of GW170817 in both gravitational waves and electromagnetic waves represents the first ‘multi-messenger’ astronomical observation. Such observations enable GW170817 to be used as a ‘standard siren’^{14–18} (meaning that the absolute distance to the source can be determined directly from the gravitational-wave measurements) to measure the Hubble constant. This quantity represents the local expansion rate of the Universe, sets the overall scale of the Universe and is of fundamental importance to cosmology. Here we report a measurement of the Hubble constant that combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using the electromagnetic data. In contrast to previous measurements, ours does not require the use of a cosmic ‘distance ladder’¹⁹: the gravitational-wave analysis can be used to estimate the luminosity distance out to cosmological scales directly, without the use of intermediate astronomical distance measurements. We determine the Hubble constant to be about 70 kilometres per second per megaparsec. This value is consistent with existing measurements^{20,21}, while being completely independent of them. Additional standard siren measurements from future gravitational-wave sources will enable the Hubble constant to be constrained to high precision.

this galaxy allow us to estimate the appropriate value of the Hubble flow velocity. Because the source is relatively nearby, the random relative motions of galaxies, known as peculiar velocities, need to be taken into account. The peculiar velocity is about 10% of the measured recessional velocity (see Methods).

The original standard siren proposal¹⁴ did not rely on the unique identification of a host galaxy. By combining information from around 100 independent gravitational-wave detections, each with a set of potential host galaxies, an estimate of H_0 accurate to 5% can be obtained even without the detection of any transient optical counterparts²². This is particularly relevant, because gravitational-wave networks will detect many binary black-hole mergers over the coming years²³ and these are not expected to be accompanied by electromagnetic counterparts. Alternatively, if an electromagnetic counterpart has been identified but the host galaxy is unknown, then the same statistical method can be applied but using only those galaxies in a narrow beam around the location of the optical counterpart. However, such statistical analyses are sensitive to several complicating effects, such as the incompleteness of current galaxy catalogues or the need for dedicated follow-up surveys, and to a range of selection effects²⁴. Here we use the identification of NGC 4993 as the host galaxy of GW170817 to perform a standard siren measurement of the Hubble constant^{15–18}.

Analysis of the gravitational-wave data associated with GW170817 produces estimates for the parameters of the source, under the assumption that general relativity is the correct model of gravity³. We are most interested in the joint posterior distribution on the luminosity distance and binary orbital inclination angle. For the analysis we fix the location of the gravitational-wave source on the sky to the identified location of the counterpart⁸ (see Methods for details).

An analysis of the gravitational-wave data alone finds that GW170817 occurred at a distance $d = 43.8^{+2.9}_{-6.9}$ Mpc all values are

Summary: Measuring Cosmological Parameters.

- Measuring the Hubble constant using nearby galaxies requires corrections for peculiar motions (i.e. attraction between galaxies)
- Distances to nearby galaxies are determined by bootstrapping empirical distance indicators to direct distance measurements. This is known as the distance ladder.
- Type Ia Supernovae are the best standard candle that can be seen at large distances (i.e. $z \sim 1$). Measurements of the brightness and redshift indicate a negative deceleration parameter.
- We live in an accelerating universe! And Einstein's cosmological constant is back in fashion.
- Multi-messenger astrophysics, combining observations of both gravitational waves and EM radiation of NS-NS mergers, will directly measure H_0 .