Hubble tension

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Hubble law

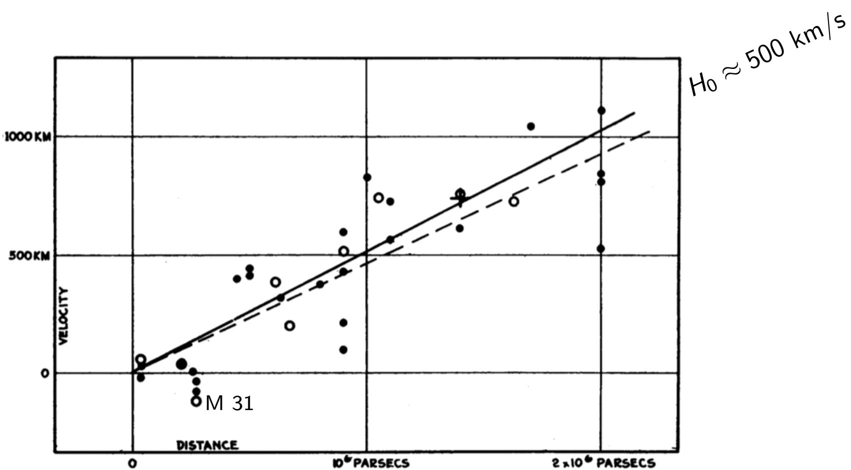


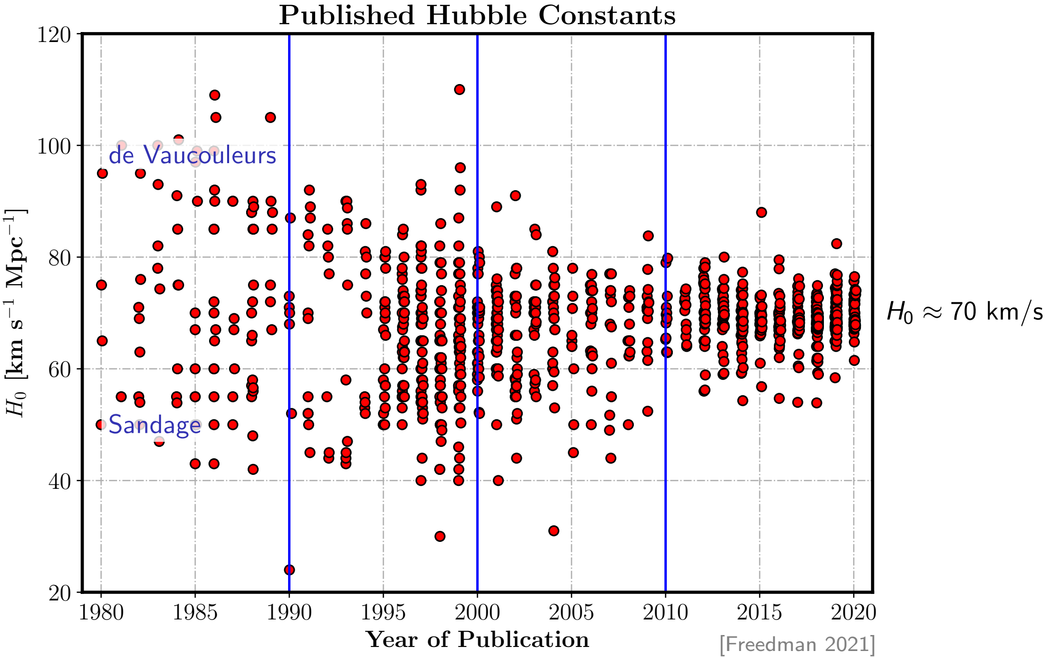
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae. [Hubble 1929]

Expansion of the Universe: recess velocity of galaxies $V \approx H_0\, D$

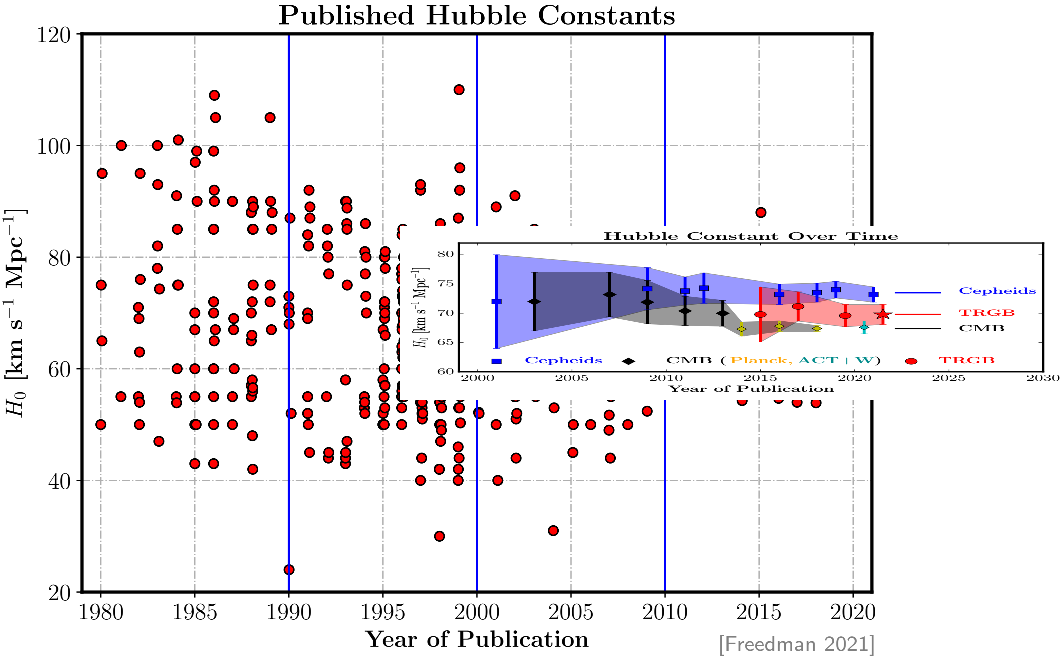
(also discovered by Lemaître 1927; see e.g. van den Bergh 2011 for a historical perspective).

Hubble constant measurements over time



[Freedman 2021]

Hubble constant measurements over time



[Freedman 2021]

Expansion of the Universe

Redshift z or scale factor $a \equiv 1/(1+z)$ satisfy the Friedmann equation

$$\frac{\mathrm{d}a}{\mathrm{d}t} = H_0\, a\sqrt{\Omega_\Lambda + \Omega_m a^{-3} + \Omega_r a^{-4}},$$

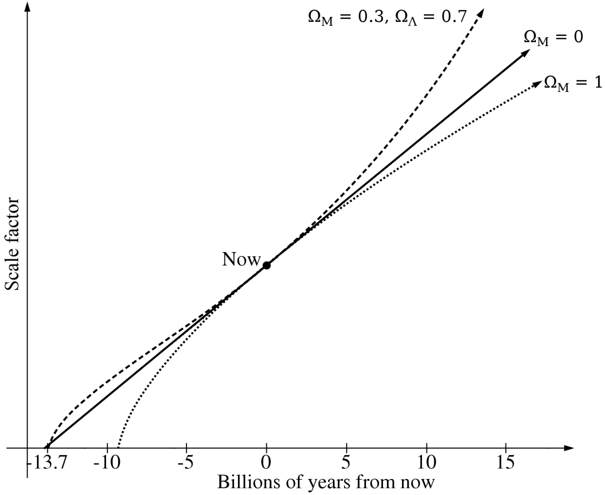
where $\Omega_\Lambda, \Omega_m, \Omega_r$ are the present-day densities of dark energy, matter (baryons and dark matter together) and radiation.

The Hubble *parameter* is

$H(t) \equiv \dot{a}(t)/a(t)$,

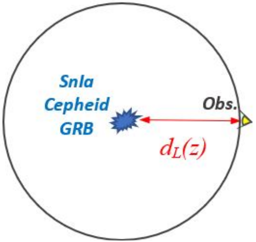
and H_0 is its value at present time.

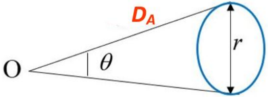
Its dimension is time^{-1}, and the reciprocal quantity $T_{\mathrm{Hubble}} \equiv H_0^{-1}$ is comparable to the age of the Universe.



Standard candle and standard ruler

- The *luminosity distance* D_L relates the intrinsic luminosity L of an object to the observed flux $F = \dfrac{L}{4\pi\, D_\mathrm{L}^2}$.
- The *angular diameter distance* D_A relates the intrinsic size of an object R to its apparent angular size $\theta = \dfrac{R}{D_\mathrm{A}}$.

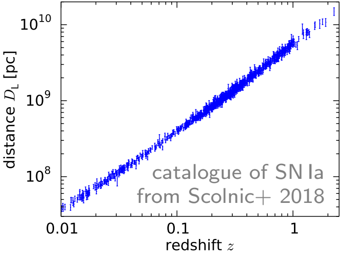




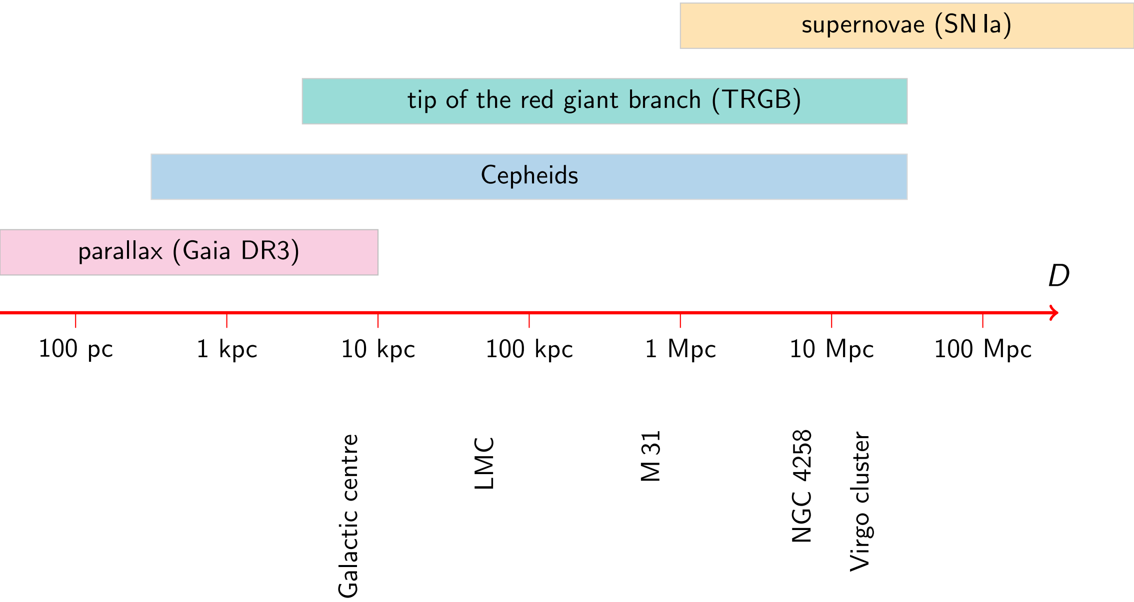
In an expanding Universe, these two concepts are not identical and depend on the expansion history:

$$D_\mathrm{L}(z) = c\,(1+z)\int_0^z \frac{\mathrm{d}z'}{H(z')}, \qquad D_\mathrm{A}(z) = (1+z)^2\, D_\mathrm{L}(z).$$

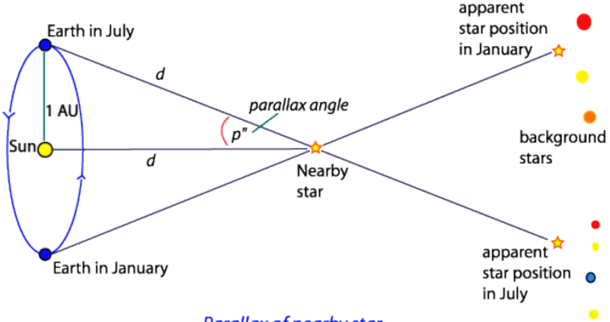
By measuring distances for objects with known intrinsic luminosity ("standard candles") or size ("standard rulers") and plotting their distance against redshift, we can measure $H(z)$ or $H(t)$.



Measuring distances: cosmic distance ladder



Parallax

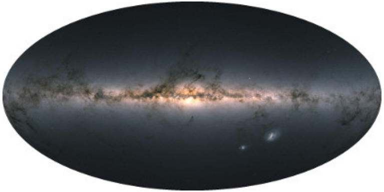


Parallax of nearby star

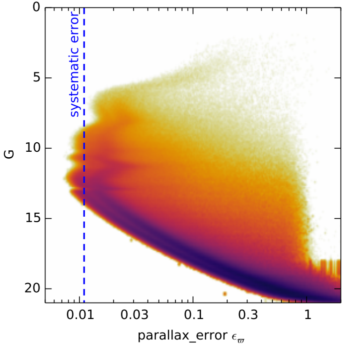
Parallax is a direct geometric measure of distance: $\varpi = 1/D \quad$ (1 mas $\Leftrightarrow$ 1 kpc).

Gaia satellite provides parallaxes for $\gtrsim 1.5 \times 10^9$ stars in the Milky Way and beyond, with the measurement uncertainty ~ 0.01 mas for bright sources.

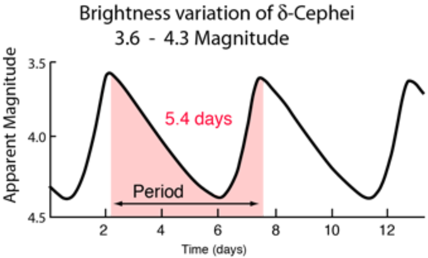
The caveat is a small systematic offset at the level 0.01 mas, which varies with magnitude, colour and sky position.

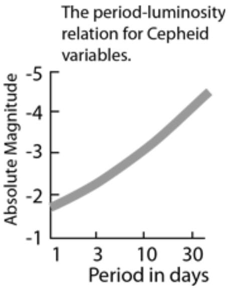


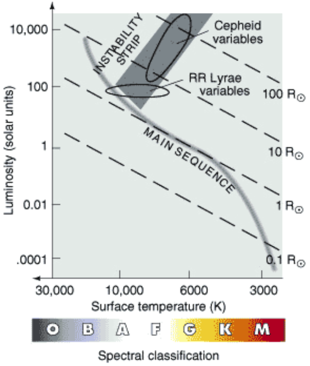
Gaia DR3 sky map [credit: ESA]



Cepheid variable stars





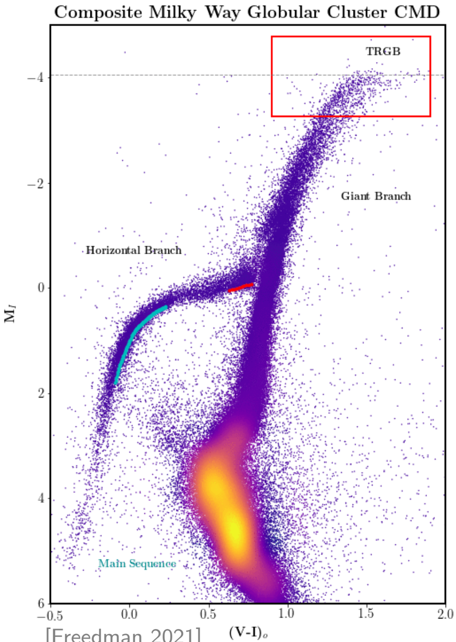


Cepheids are bright supergiants with regular pulsations, the relation between their period and absolute luminosity discovered by Leavitt (1908).

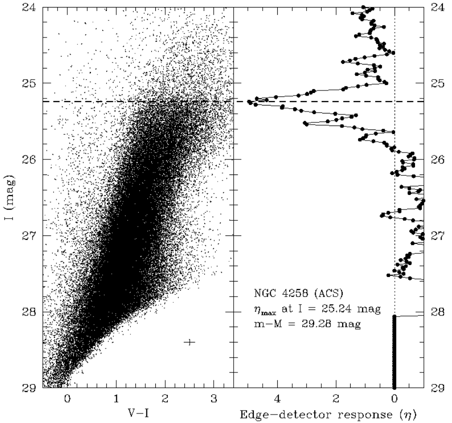
The closest ones have well-measured Gaia parallaxes, while the most distant can be observed with HST up to a few tens Mpc.

Caveats include the need for multi-epoch observations, metallicity dependence of absolute magnitudes, and crowding in distant galaxies.

Tip of the red giant branch (TRGB)



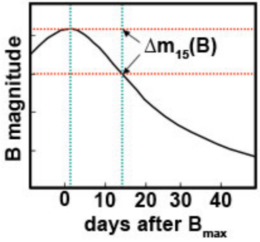
[Freedman 2021]

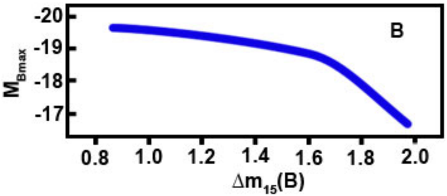


[Mager+ 2008]

The bright magnitude limit of red giant branch is calibrated using distances to Milky Way globular clusters and can be measured in galaxies up to a few tens Mpc.

Type Ia supernovae



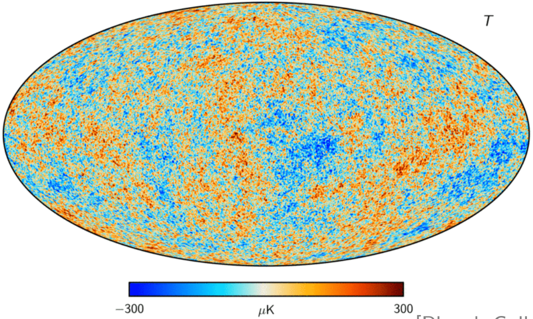


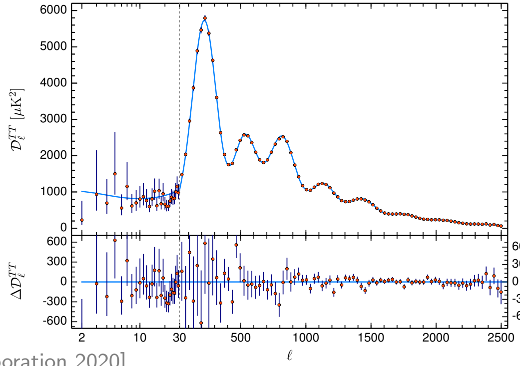
SN Ia are produced by thermonuclear explosions of white dwarfs whose mass exceeds the Chandrasekhar limit ($\sim 1.4\, M_{\odot}$) as a result of accretion from a companion star or a merger with another white dwarf.

They are very bright and can be observed up to $z = 2$, and the peak absolute magnitude is related to the decay time [Tripp & Branch 1999].

Caveats: possible dependence of peak magnitude on redshift and host galaxy mass.

Cosmic microwave background





[Planck Collaboration 2020]

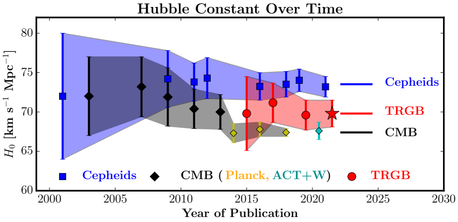
Parameter	value (Planck 2018)
baryon density Ω_b	0.049 ± 0.001
dark matter density Ω_c	0.261 ± 0.005
age of the Universe t_0	13.787 ± 0.02 Gyr
spectral index n_s	0.965 ± 0.004
reionization optical depth τ	0.054 ± 0.007
Hubble parameter H_0	67.4 ± 0.5 km/s

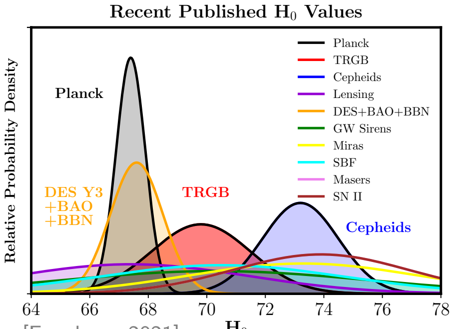
} standard cosmological model (ΛCDM)

H_0 is mainly determined by the distance between peaks in the CMB spectrum.

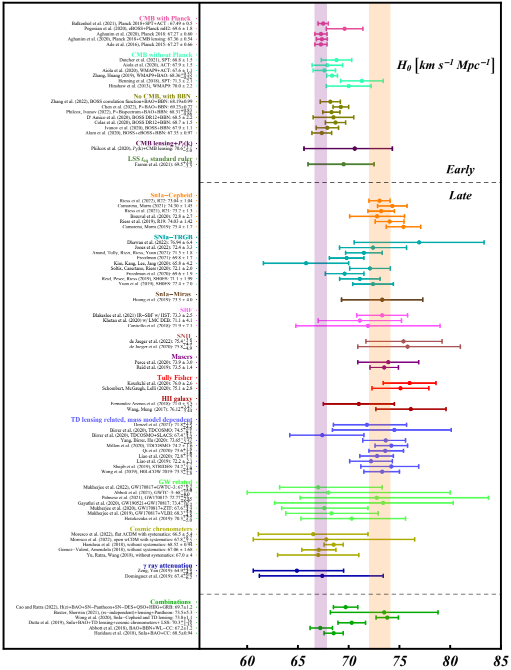
The Hubble tension

Early (CMB) and late (local Universe) measurements of H_0 disagree at $\sim$ 4–5σ.





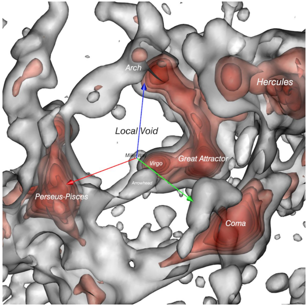
[Freedman 2021]



[Perivolaropoulos & Scara 2022]

Possible explanations

- New physics in the early Universe (before recombination), e.g., extra sort of neutrinos
  – but it is difficult to maintain an excellent fit to the CMB power spectrum, satisfy nucleosynthesis constraints, etc.
- New physics in the late Universe (e.g., a nontrivial dark energy EoS or variation of fundamental constants)
  – but it has numerous undesirable properties, like the "big rip" scenario.
- "Local bubble": inhomogeneities in the local Universe at scales of tens of Mpc
  – but the discrepancy persists on much larger scales.
- Calibration issues in the distance ladder
  – a lot of effort has been devoted to combat these, but some systematic offsets still remain possible.

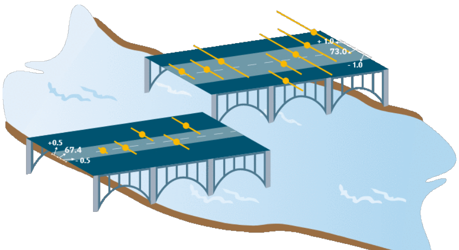


Summary

We discussed...

- Cosmic distance ladder
- Standard[izable] candles
- New physics or calibration issues?

Several conferences have been dedicated specifically to the Hubble tension, and the question still remains open...



Cosmology at the crossroads (2021)

If you want to know more...

Astron Astrophys Rev (2021) 29:9
https://doi.org/10.1007/s00159-021-00137-4

REVIEW ARTICLE

A buyer's guide to the Hubble constant

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Abstract

Since the expansion of the universe was first established by Edwin Hubble and Georges Lemaître about a century ago, the Hubble constant H_0 which measures its rate has been of great interest to astronomers. Besides being interesting in its own right, few properties of the universe can be deduced without it. In the last decade, a significant gap has emerged between different methods of measuring it, some anchored in the nearby universe, others at cosmological distances. The SH0ES team has found $H_0 = 73.2 \pm 1.3$ kms^{-1} Mpc^{-1} locally, whereas the value found for the early universe by the Planck Collaboration is $H_0 = 67.4 \pm 0.5$ kms^{-1} Mpc^{-1} from measurements of the cosmic microwave background. Is this gap a sign that the well-established ΛCDM cosmological model is somehow incomplete? Or are there unknown systematics? And more practically, how should humble astronomers pick between competing claims if they need to assume a value for a certain purpose? In this article, we review results and what changes to the cosmological model could be needed to accommodate them all. For astronomers in a hurry, we provide a buyer's guide to the results, and make recommendations.

arxiv.org/abs/2109.01161