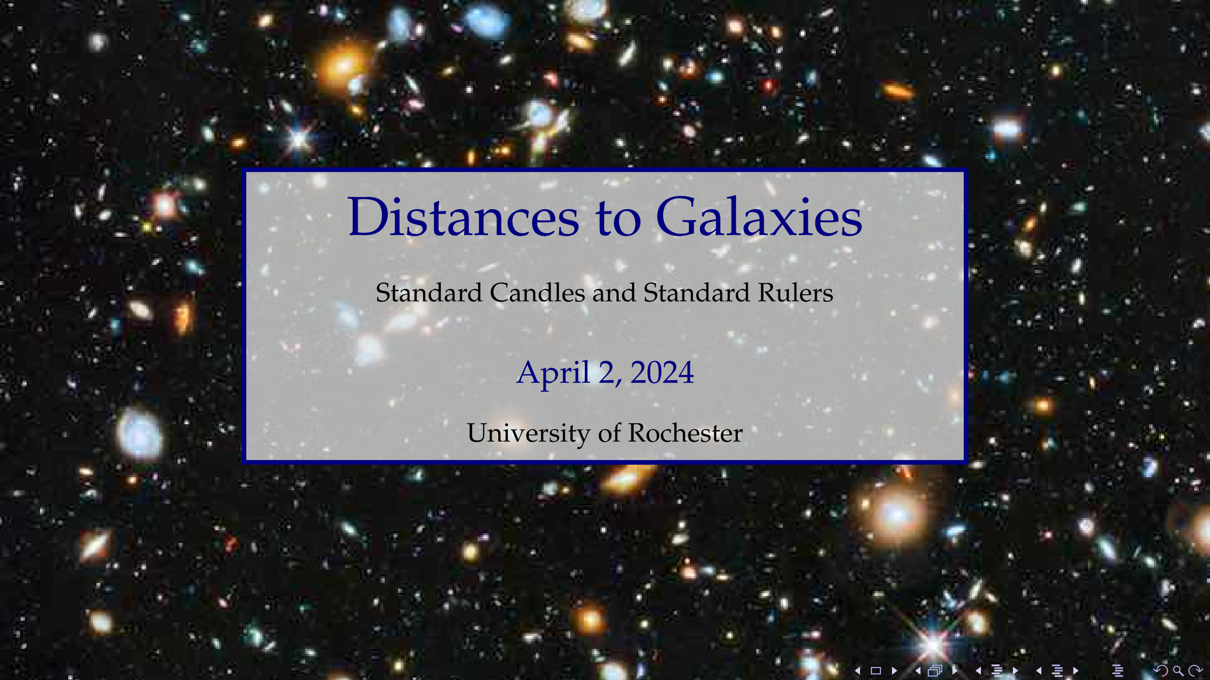


Distances to Galaxies

Standard Candles and Standard Rulers

April 2, 2024

University of Rochester

Distances to galaxies

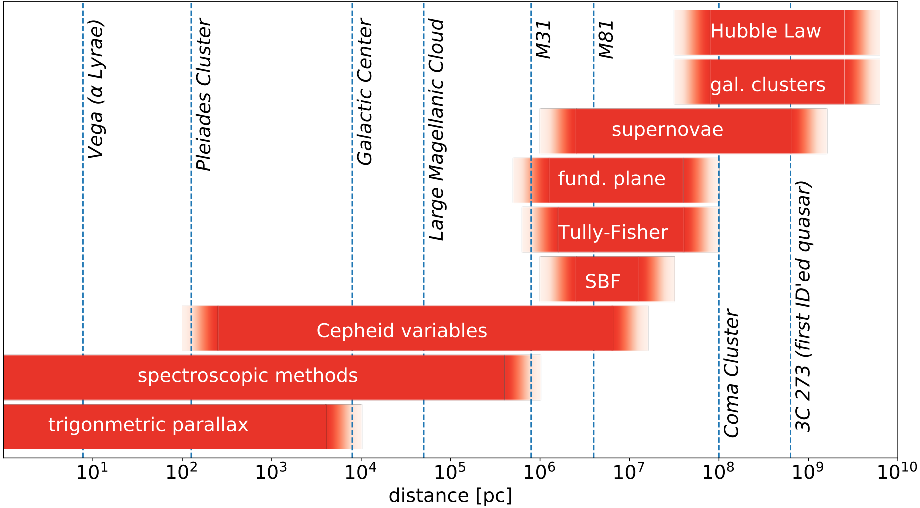
- Standard candles and standard rulers
- Leavitt's invention of standard candles: Cepheids
- The extragalactic nature of spiral nebulae: the Shapley-Curtis debate
- Standard candles: Type Ia supernovae
- The extragalactic distance scale

Reading: Kutner Sec. 12.2, 18.1–18.3, & 20.5, Ryden Sec. 20.4

Right: the SMC, site of the discovery of Leavitt's Law. Photograph by Wei-Hao Wang, NRAO.

The distance ladder

Distances from galactic to extragalactic scales.



Standard candles & standard rulers

There is only one **direct** distance measurement for objects beyond a few light-hours away: **trigonometric parallax**, and it only works on relatively unextinguished objects within about 100 kpc of us (e.g., *Gaia*). To measure distances beyond this, we use standard candles or rulers.

Standard Candle An object with a well-determined luminosity L known *a priori*, and measurable flux f, whose distance is therefore

$$r = \sqrt{\frac{L}{4\pi f}} \qquad \text{or equivalently} \qquad r = 10^{(m-M)/5+1}\ \text{pc}$$

Standard Ruler An object with length d perpendicular to the line of sight known *a priori*, and measurable angular size θ, whose distance is

$$r = \frac{d}{\sin\theta} \approx \frac{d}{\theta}$$

Discovery of standard candles

Cepheid variables were the first standard candles. Today, $> 10^4$ are known. A large fraction of them (2400) were identified by **Henrietta Leavitt**, who worked as a "computer" in Edward Pickering's group at Harvard College Observatory.

- 969 of Leavitt's Cepheid variables are in the SMC (Leavitt 1908), so they are all $\sim$60 kpc away.
- Leavitt noticed in the first few sets of photographic plates that many of the brightest stars were variable and that the brighter variables had longer periods.
- She also noticed that the light curve *shapes* resemble those of "cluster variables," the stars we now call RR Lyrae variables. The Milky Way globular cluster 47 Tuc was in all of her SMC plates.

Discovery of standard candles

After noticing the brightness-period relation, Leavitt acquired ∼100 more plates on the SMC, taken over a period of 16 years, from the Harvard archives. She then worked out the light curves and periods of many of the variables.

Choosing 25 objects with particularly good light curves and a large range of magnitudes, Leavitt determined their periods and showed that the **magnitudes are proportional to the logarithm of the periods** (Leavitt & Pickering 1912).

Conclusion: The variables are **standard candles** —

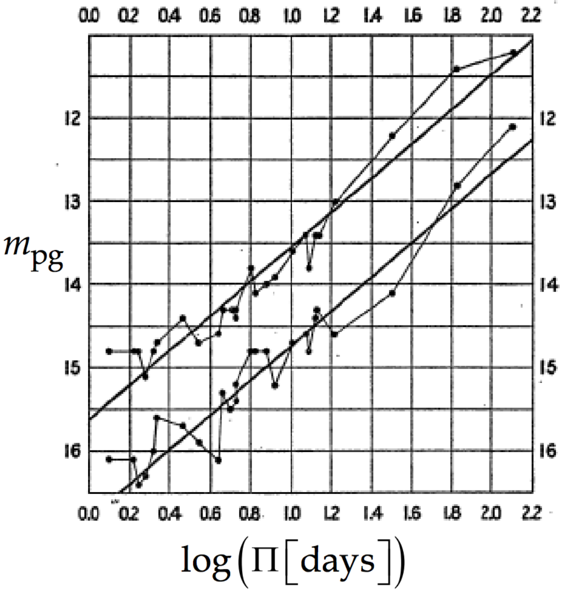
> *Since the variables are probably at nearly the same distance from Earth, their periods are associated with their actual emission of light [luminosity], as determined by their mass, density, and surface brightness.*

Discovery of standard candles

Period–apparent magnitude relation for the bright variables in the SMC, from Leavitt & Pickering (1912).

The upper (lower) curve represents each star's maximum (minimum) brightness in its pulsation cycle.

The linear fits have the same slope: 1 mag per 0.48 in $\log(\Pi/\mathrm{day})$.



Discovery of standard candles

Today, we know that Leavitt's stars are classical Cepheids (not RR Lyraes) and the period–average magnitude relation for her LMC stars is (Monson et al. 2012)

$$\overline{m_V}(\mathrm{LMC}) = -2.77 \log\left(\frac{\Pi}{\mathrm{day}}\right) + 17.58$$

Since the absolute and apparent magnitudes differ only by the constant distance modulus and the V extinction — 18.48 and 0.39 mag, respectively, for the LMC — we have a relation between the period and absolute magnitude (**Leavitt's Law**):

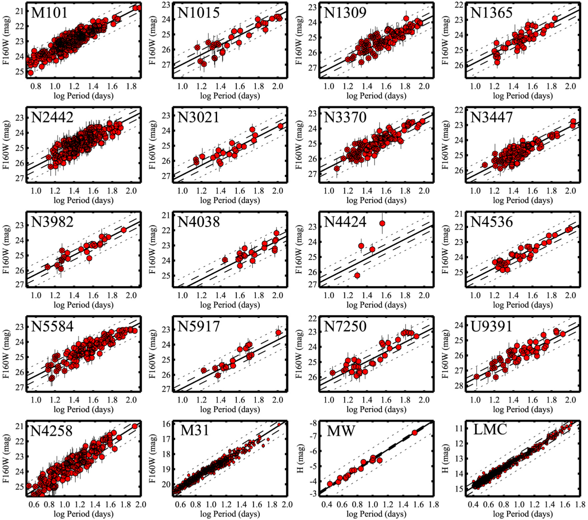
$$\overline{M_V}(\Pi) = -2.77 \log\left(\frac{\Pi}{\mathrm{day}}\right) - 1.69$$

and the distance to a new Cepheid with period Π is given by

$$5 \log\left(\frac{r}{10\ \mathrm{pc}}\right) = \overline{m_V} - \overline{M_V}(\Pi)$$

Discovery of standard candles

Leavitt's Law for 23 galaxies (Riess et al. 2016)



Cepheids & the size of the Galaxy (1918)

As Leavitt's work enabled astronomers to measure distances outside the Milky Way, it counts as one of the most important discoveries in modern science.

Harlow Shapley (Pickering's successor as director of Harvard College Observatory) recognized the importance of Leavitt's Law and set about extrapolating it as a standard candle for distances to globular clusters.

Shapley correctly identified the variability of Cepheids as radial pulsation instead of binary variations (Shapley 1914), but he did not realize (and could not have known) that there were so many different kinds of pulsating stars with similar periods and different luminosities.

- The regular variable stars in globular clusters (RR Lyraes and W Virginis stars) are much less luminous than classical Cepheids.

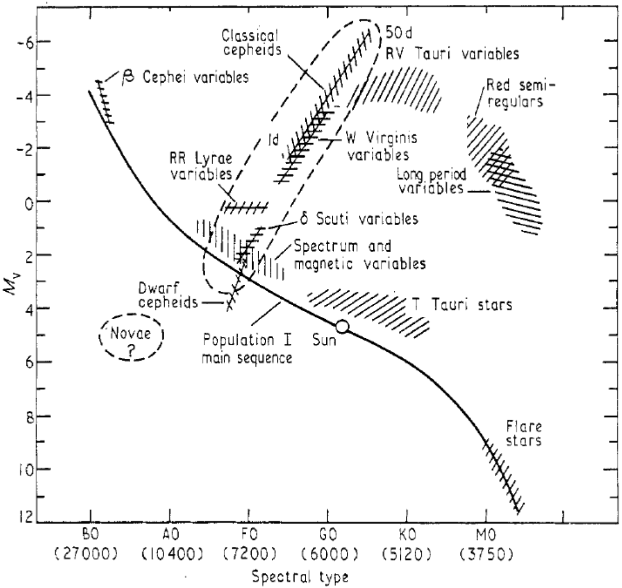
Nor did Shapley know about interstellar extinction; in fact, he thought he had ruled it out (Shapley 1917) as an effect that would make the Galaxy look larger than it really is.

Hindsight on the pulsating stars

Classical Cepheids belong to Pop I: high metallicity, low random velocity.

W Virginis stars and RR Lyraes belong to Pop II: low metallicity, high random velocity.

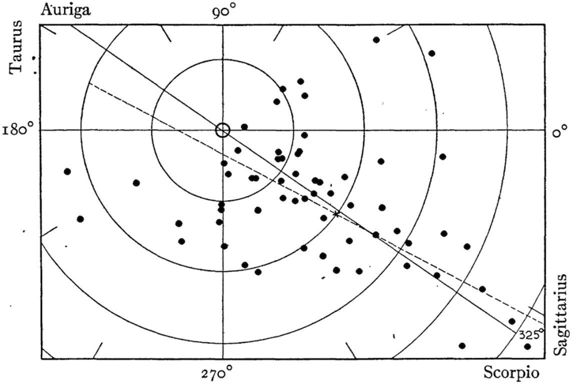
Right: H-R diagram of pulsating stars from Cox (1974), with the **Instability Strip** indicated by the dashed line.



Cepheids & the size of the Galaxy (1919)

Thus Shapley determined the *shape* of the distribution of globular clusters correctly, and he found our relative offset from the center of the Galaxy, but his Galaxy diameter exceeded 100 kpc (Shapley 1918).

By these measures, the Magellanic Clouds were within the Milky Way, consistent with contemporary ideas that the LMC and SMC were unusually large Galactic stellar clusters.



Globular cluster analysis by Shapley (1919). Dots are positions of globular clusters projected onto the plane of the MW. Circles are galactocentric radii in intervals of 10 kpc.

Spiral nebulae: Galaxies or not?

The Galactic diameter seemed so enormous to Shapley that he and many others began to think it ruled out the "island universe" description of spiral nebulae first put forward by Immanuel Kant in 1755 (Kant 1755).

Shapley's conclusion: the spiral nebulae are not distant objects similar in size to the Milky Way (Shapley 1919).

Spiral nebulae are what we now call *spiral galaxies*. The following was known about the spiral nebulae 100 years ago:

- They come in different shapes and sizes. Some viewed edge-on closely resemble the Milky Way.
- They were not resolved into individual stars.
- Like globular clusters, they "avoid" the Galactic plane and are only observed at relatively high Galactic latitude.

Spiral nebulae: Galaxies or not?

Using new and much more sensitive telescopes than previously available, attention turned to the faintest interesting objects like spiral nebulae.

- "Flares" were observed in a few spiral nebulae — e.g., S Andromedae, M31, 1885 — and as they were similar in brightness to **novae**, they were suggested to be Galactic.
- Van Maanen (1916) reported rotational proper motion of the spiral arms of the big Sc galaxy M101. The corresponding rotation period was 10^5 years; if it were extragalactic the rotation speeds would be relativistic.
- All but a few spiral nebula — the ones with the largest angular size — were shown by Slipher (1917) to recede from the LSR at speeds much larger than typical for Galactic stars.

The Shapley-Curtis debate

These observations led to the celebrated Shapley-Curtis “debate” in the April 1920 meeting of the Council of the National Academy of Sciences.

Both Shapley and Heber Curtis presented 40-minute talks on distances in the Universe and whether the spiral nebulae were extraglactic.

Shapley	Spiral nebulae lie within the Galaxy.
Curtis	Nah

It was not actually a debate, but both Shapley and Curtis wrote up their arguments at great length for wide distribution (Shapley & Curtis 1921).

(See Hoskin (1976) for a less dramatic account of the debate.)

Spiral nebulae are extragalactic

The issue was laid to rest only a few years later when Edwin Hubble detected pulsating variable stars in the big spirals M31 (Andromeda) and M33 (Triangulum) (Hubble 1925).

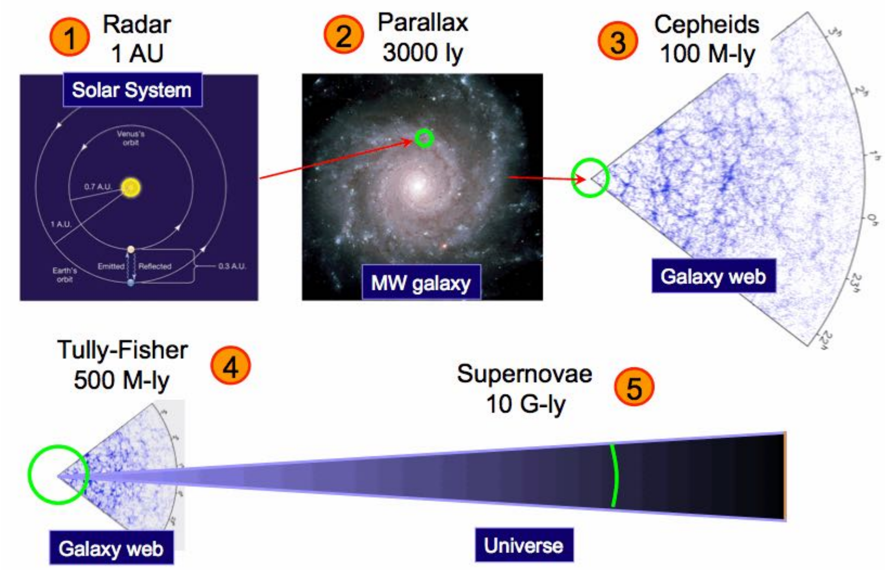
- Hubble's observations showed that these nebulae are 10 times further from us than the distance to the Galactic center, derived in the same way by Shapley.
- With hindsight, we know this distance was actually *too small* for the same reason Shapley's distances were too large: the assumption that variables in globular clusters were the same as classical Cepheids seen in M31, M33, and the Magellanic clouds.
- Regardless of precise distance, the results proved a large **ratio** for the M31 or M33/Galactic center distances, far too large for them to lie within the Milky Way.

Spiral nebulae are extragalactic

What about the novae, M101's relativistic rotation, the high recession speeds, and the Galactic plane avoidance of the spirals?

- The flares in spirals turned out to be **supernovae**, named and correctly explained by Baade & Zwicky (1934). S Andromedae turned out to be a SN Ia.
- Van Maanen's proper motion measurements were shown by Hubble and van Maanen himself to be in error (Hubble 1935, VanMaanen 1935).
- Slipher's recession measurements held up; **the galaxies are nearly all receding from the Milky Way** and are doing so at high speed. These results were used to great effect by Hubble in the late 1920s.
- Trumpler's discovery of interstellar extinction (Trumpler 1930) explained the absence of spiral nebulae in the Galactic plane, as well as problems in the Cepheid period-luminosity calibration.

The extragalactic distance scale



① Radar
1 AU

Solar System

② Parallax
3000 ly

MW galaxy

③ Cepheids
100 M-ly

Galaxy web

Tully-Fisher
500 M-ly ④

Galaxy web

Supernovae
10 G-ly ⑤

Universe

The extragalactic distance scale

The ladder by which distances to celestial objects are currently determined. Each rung depends on the previous result, inheriting its uncertainty and adding its own.

1. Distances at the scale of AU are measured using **radar** reflection from Venus and Mars, and now time-stamped spacecraft radio transmissions.
   - It would be tempting to measure stellar distances by radar, but the reflected signal decreases as r^{-4}, so it does not work for objects more than a few light-hours away.

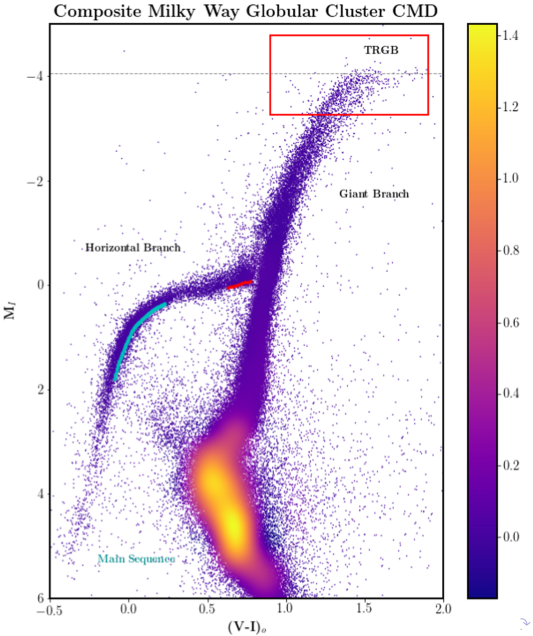
2. Use **trigonometric parallax** to determine the distances to as many variable stars (e.g., classical Cepheids, RR Lyr) as possible, and work out the terms in Leavitt's Law (for the classical Cepheids).
   - With *Gaia*, there are about 200 Cepheids with decent parallax measurements in DR2 (Groenewegen 2018).
   - More than 20 times as many as can have distances measured by main-sequence fitting (An et al. 2007), and more accurate besides.

The extragalactic distance scale

2b. RR Lyr are not as bright as classical Cepheids, so we observe as many globular clusters as possible, measuring their distances with RR Lyr stars as standard candles.

2c. Measure the HR diagram of each globular cluster, and from these, calibrate a new standard-candle luminosity, the **tip of the red giant branch** (TRGB).

- Unlikely as it seems, the luminosity of the TRGB is remarkably uniform.



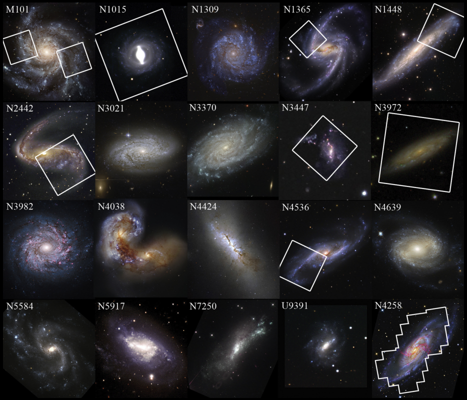
Freedman (2021)

The extragalactic distance scale

3. Observe classical Cepheid periods and fluxes, or the TRGB, in galaxies, get their luminosities from their periods (Cepheids), and determine their distances (and therefore distances to their host galaxies) using

$$r = \sqrt{\frac{L}{4\pi f}}$$

- This works until it is impossible to isolate individual stars in the galaxy disks. For ground-based telescopes, the limit is about 3 Mpc. For the HST, the distance limit is about 40 Mpc.



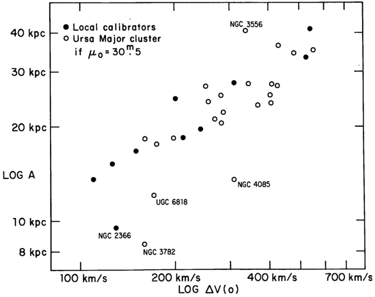
NGC 3370 has at least 93 Cepheids (Hoffmann et al. 2016)

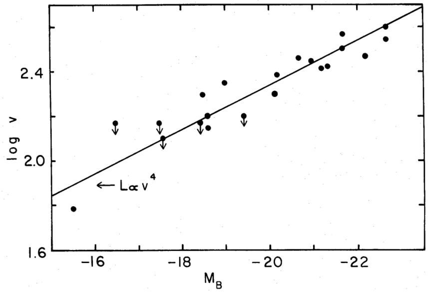
The extragalactic distance scale

4. Near the end of the Cepheid & TRGB range, several empirical relations are used to calibrate galactic luminosity and distance:

   Tully-Fisher relation Power law relation between the rotation speed of a spiral galaxy and its mass or intrinsic luminosity (Tully & Fisher 1977).

   Faber-Jackson relation Power law relation between the velocity dispersion of elliptical galaxies and their intrinsic luminosity (related to "fundamental plane" relations for ellipticals) (Faber & Jackson 1976).

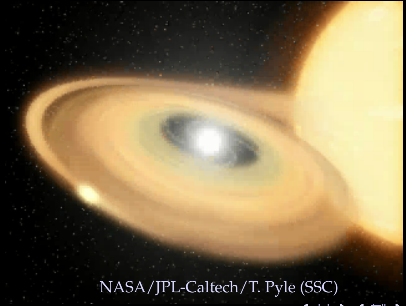




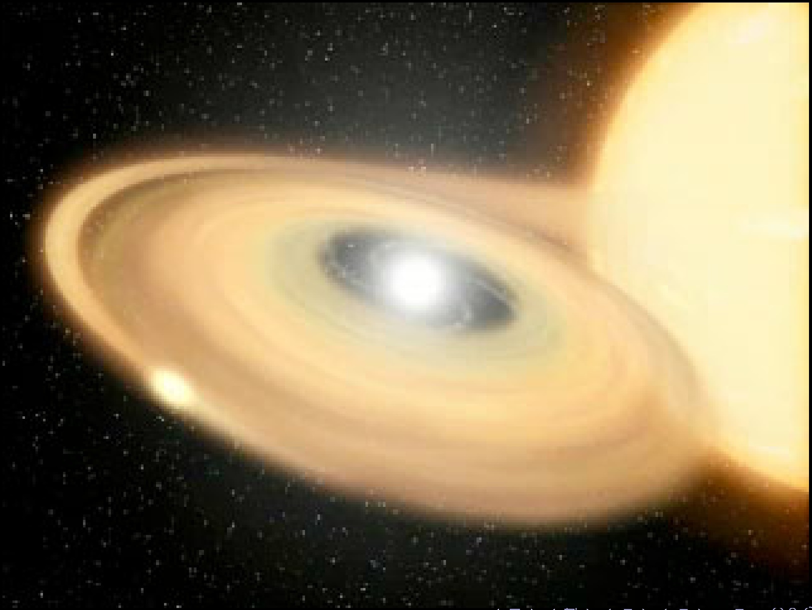
The extragalactic distance scale

5. In the 20–40 Mpc range, we begin to find significant numbers of galaxies with both Cepheids and observed **Type Ia supernovae**.
   - SNe Ia differ observationally from core-collapse supernovae (SNe II) by the shape of their light curves (luminosity vs. time) and their spectra (luminosity vs. wavelength) near maximum light.
   - A different explosive process has been inferred for SNe Ia, which occur in close binary systems with a C-O white dwarf accreting mass from its main-sequence or giant companion.


NGC 3370: NASA/ESA/HST


NASA/JPL-Caltech/T. Pyle (SSC)

Dwarf Novae



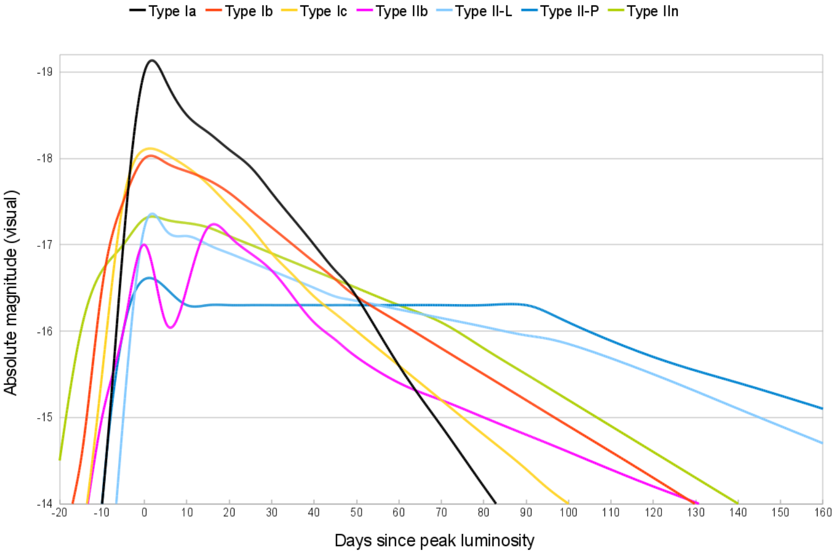
Dwarf nova: accretion adds heat and hydrogen but the WD does not expand in response. So a very hot surface region develops in which fusion (and a thermonuclear explosion) can occur, resulting in a month-long ~ 3 mag brightening of the system.

Type Ia supernovae: Standard candles

- Despite punctuation by nova outbursts, the accretion process can keep the WD increasing in mass, eventually reaching M_{SAC}.
- Near M_{SAC}, the temperature of the nondegenerate nuclei increases along with the accreted hydrogen on the WD surface.
- Eventually, at about $1.3M_\odot$, C-C fusion begins. This becomes a runaway thermonuclear deflagration that consumes the entire star. It explodes violently and leaves no remnant.
- The explosion is *very* bright — more than a SN II at its peak — and can outshine the rest of the host galaxy.
- Because of the constancy of M_{SAC}, the WDs all have very nearly the same mass when they explode, and therefore the same "yield." SNe Ia are another **standard candle**. Thus, for a given distance, the integral over the SN Ia light curve should vary little between explosions.

Reminder: Supernova light curves

SNe II have the same *average* integrated output as SNe Ia, but with a much lower peak and much more variation.



SN Ia distance calibration

To calibrate the distance ladder, astronomers observe galaxies with both Cepheids and SNe Ia, measuring the distances to the supernovae with the Cepheids.

Once the calibration is performed, the distance is known to any galaxy containing an SN Ia.

Calibration of 42 SNe Ia using Cepheid variables in the host galaxies. From Riess et al. (2021).