2. Stars
Stellar structure and evolution

8, 15 février 2024

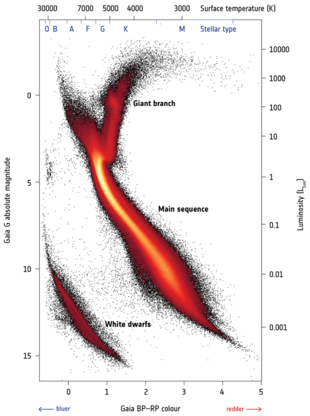
UGA L3 — Introduction to astrophysics

---

1 Stars

- ▷ The form, evolve, and die
- ▷ *One property to rule them all*: **the mass**
  - All properties (luminosity, temperature, lifetime) depend primarily on a single property: the mass of the star when it stars shining
- ▷ Understanding of stars
  - Spectroscopy
  - Quantum physics, nuclear and particle physics, thermodynamics, statistical physics
  - A major achievement of XXth century physics

The Hertzsprung-Russel Diagram (HRD)



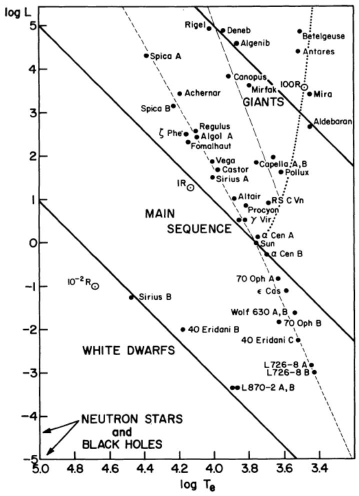
Our Lecture: understand the physical basis of the HRD

Basics of the HRD

- ▷ Vertical scale: Luminosity $\mathscr{L}$ or absolute magnitude
- ▷ Horizontal scale: Effective temperature of spectral type
- ▷ Fundamental relation:

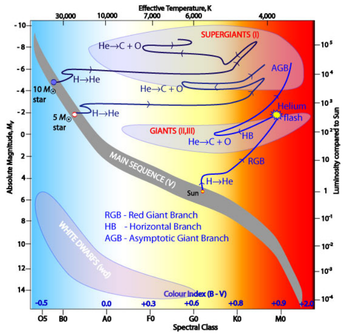
$$\mathscr{L} = 4\pi R^2 \sigma T_{\rm eff}^4$$

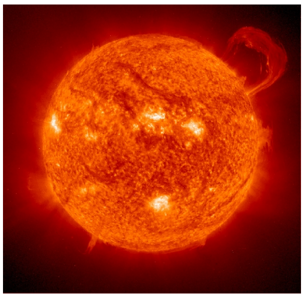
  - $\mathscr{L}$ in Watt, R: radius; σ = Stefan-Boltzman constant = 5.67×10^{-8} W m^{-2} K^{-1}, $T_{\rm eff}$(in K): effective temperature of the blackbody ≈ temperature of the photosphere



2

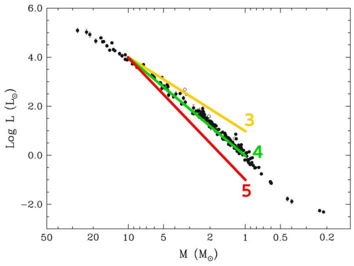
Main sequence stars





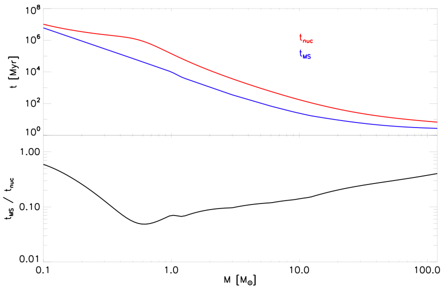
- ▷ A star spends most of the time on the *main-sequence*
  - MS = fusion of hydrogen into helium
  - The Sun spends 10 Gyr on the MS
  - Massive stars spend less time on the main sequence

Mass-Luminosity relation



- ▷ Mass is the primary property of a star
- ▷ All stars work pretty much the same: competition between gravity and pressure
  - Pressure is due to temperature (thermal pressur, like for a perfect gas), to radiation, and in some cases (very dense regions as in white dwarfs or neutron stars) to Pauli exclusion principle
- ▷ Luminosity is the most important property because this is what we can measure
  - L ~ M^ξ, ξ ≈3.5-4

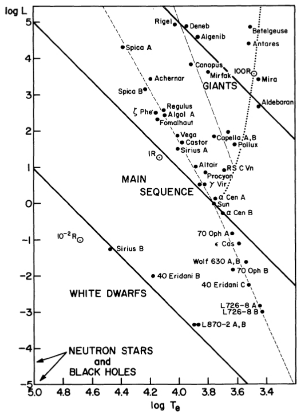
Main sequence lifetime

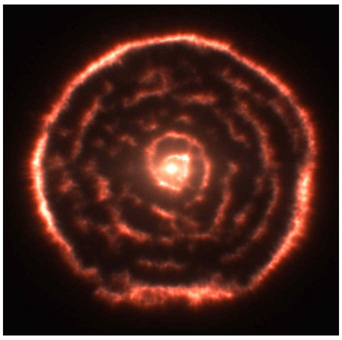


- ▷ t_{ms} ~ M/L ~ $M^{1-\xi}$
  - Reality more complex (convective vs radiative stars)
- ▷ Estimate the main-sequence lifetime of a 5 $M_\odot$ star

---

3 Post-main-sequence evolution

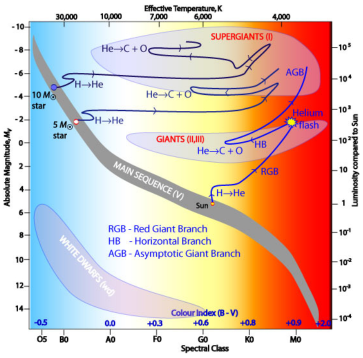




- ▷ After the main sequence: **Red Giant** star
- ▷ Example: R Sculptoris observed with ALMA; spirals=mass loss from binary

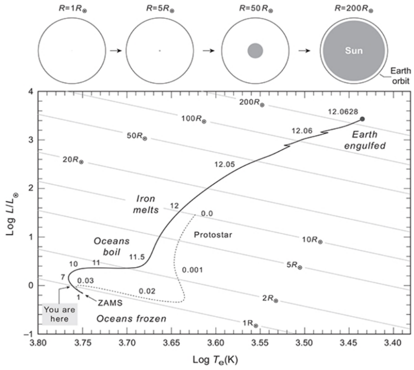
---

From hydrogen fusion to helium fusion



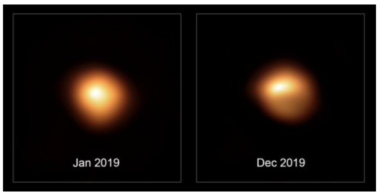
- ▷ Red Giant Branch
  - moving to the right: cooler or **redder**
  - moving upwards in the HRD: larger radius because of $\mathscr{L} = 4\pi R^2 \sigma T_{\rm eff}^4$
- ▷ After RG: burning of Helium into C and O (on the Horizontal Branch, HB)

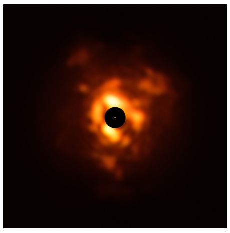
The Sun as a red giant



- ▷ The evolution of the Sun into the red giant phase
- ▷ Time is given in Gyr

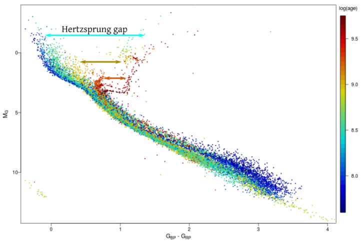
Betelgeuse

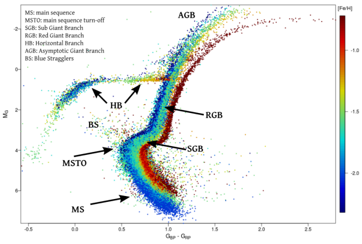




- ▷ left: visible
- ▷ right: VLT VISIR/NEAR in the infrared (10mic); dust production?

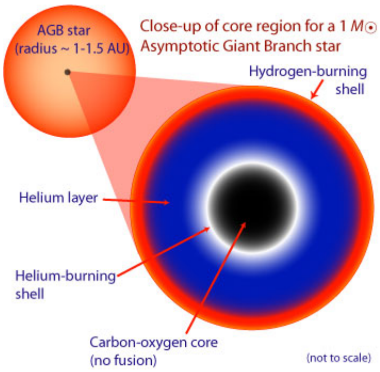
After the fusion of helium





- ▷ Helium fusion in the core of the star has stopped: cools down, moves to the right along the **Asymptotic giant branch** (AGB)
- ▷ AGB stars are stars moving on the AGB

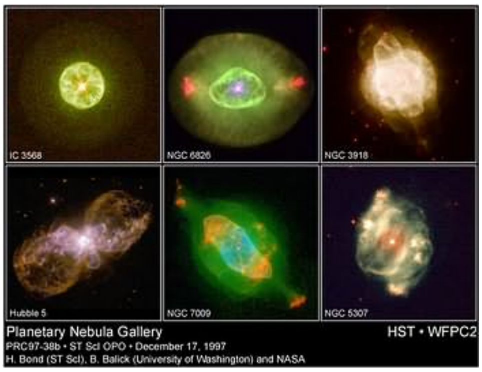
AGB stars: inner structure



- ▷ H and He shell-burning surrounding inert core of C and O
  - mass loss: **planetary nebulae**
- ▷ many other features: deep convection, neutrino cooling, s-process

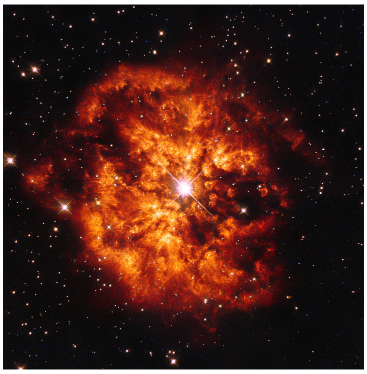
---

Planetary nebulae



- ▷ Planetary nebula are due to mass loss from AGB stars
- ▷ PN mark the end of the AGB phase

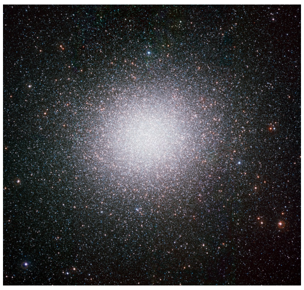
Mass loss: Wolf-Rayet stars



“WR 124 seen by the HST”

- ▷ Wolf-Rayet stars are very massive stars with extreme mass loss

4 HRD of clusters

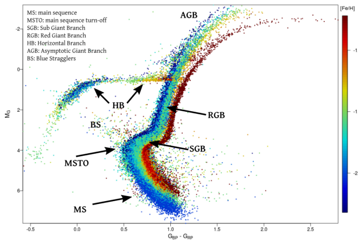


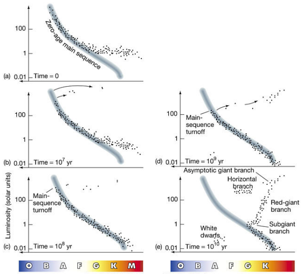
- ▷ Open clusters (left): M45, Pleiades, are young (~ 10^8 yr), 10-100 stars
- ▷ Globular clusters (right): old (~ 10^{12}-10^{13} yr)
  - Example: M1, Ω Centauri, the brightest, most massive, globular cluster in our galaxy; ~ 10^8 stars; diameter ~ 150 ly
  - revision of the coeval assumption: it is made of two populations of stars born at different times (heic0809, eso0509)

The Westerlund 1 open cluster

The Westerlund 1 open cluster, one of the largest one in the Milky Way, containing among the most massive stars, and a magnetar. More info here and here.

HRD of clusters: leaving the main sequence





Copyright © 2005 Pearson Prentice Hall, Inc.

- ▷ Key point: stars in clusters are born at ~ same time (we say they are *coeval*)
- ▷ The **main sequence turn-off** (MSTO) point; the older the cluster, the lower the MSTO in the HRD
- ▷ Visible features:
  - Hertzprung gap, subgiant, helium ignition
  - RGB; H shell-burning and He core-fusion (He flash for <2 $M_{\odot}$stars)
  - Horizontal branch (HB): helium core fusion (Helium main sequence)

5 The end of stars

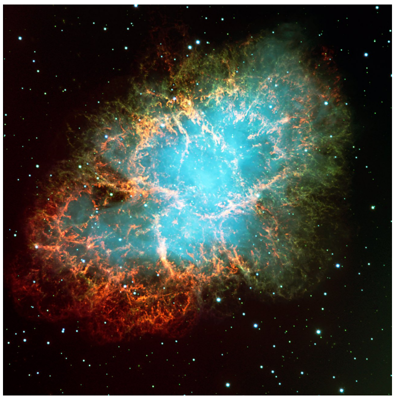
- ▷ Stellar evolution leads to different fates, **depending on the mass of the star on the main sequence**
- ▷ Quiet, slow end of life: low-mass stars (M $\leq$ 8 $M_{\odot}$)
- ▷ Cataclysmic end of life: high-mass stars (M > 8 $M_{\odot}$)
- ▷ Compact objects: white dwarfs, neutron stars, black holes

---

Low-mass stars: Planetary Nebula, White Dwarfs

- ▷ Planetary nebula are due to the loss of outer layers of AGB stars
- ▷ Central object: White dwarf (WD) are slowly cooling objects with mass $\sim$ 0.6 $M_{\odot}$and effective temperature from 10^4 to $\sim 10^5$ K.
- ▷ Image: Hubble Space Telescope

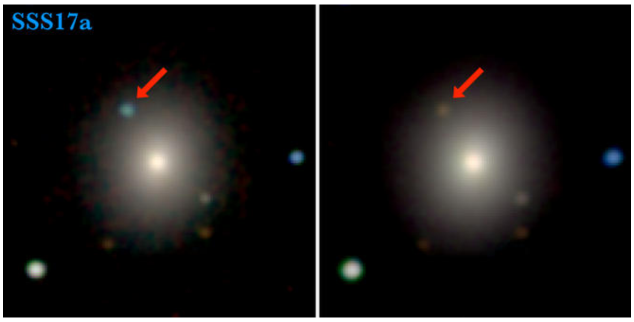
High-mass stars: Supernovae explosions, neutron stars, black holes



“Crab nebula (Messier 1), located in the Taurus, explosion in 1054 was observed and recorded by Chinese astronomers; see here *for details. Image: Very Large Telescope (VLT).”*

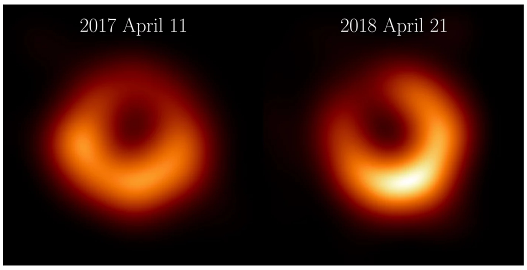
- ▷ Depending on the mass, explosion leads to **neutron star** or **black hole**
- ▷ 8 < M < 20-25 $M_{\odot}$: Supernova remnant (SNR) is a neutron star (Crab Nebula)
  - Result: a rotating neutron star (called a *pulsar*) with a period P=30ms
- ▷ Above $\sim$ 20-25 $M_{\odot}$: direct formation of a black hole

The fate of high-mass stars: Fusion of neutron stars



- ▹ Fusion of two neutron stars into a kilonova: synthesis of elements beyond iron
- ▹ First detected through gravitational waves on 17-aug-2017: fusion of a 1.1 and a 1.6 $M_\odot$ neutron stars
- ▹ Followed by multi-wavelength observations
- ▹ More information here

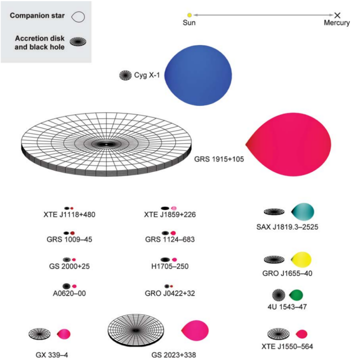
The fate of very-high-mass stars: black holes



"Direct image of a supermassive black hole by the Event Horizon Telescope (EHT)"

- ▹ Stars with main sequence mass M>20-25 $M_\odot$collapse and directly form black holes
- ▹ Broad range of black hole mass
  - stellar BH: M~ 3-20 $M_\odot$; binary systems
  - supermassive BH (SMBH): M~ 10^6 to 10^{10} $M_\odot$
  - no detection so far of Intermediate Mass BH

Stellar Black Holes



- ▹ SBHs are binary systems: companion star cover a broad range of mass too (K- to B-stars)
- ▹ In our galaxy, we estimate to $\sim 10^8$-10^9 the numbers of stellar BHs

Super Massive Black Holes

THE ASTROPHYSICAL JOURNAL, 764:184 (14pp), 2013 February 20 MCCONNELL & MA

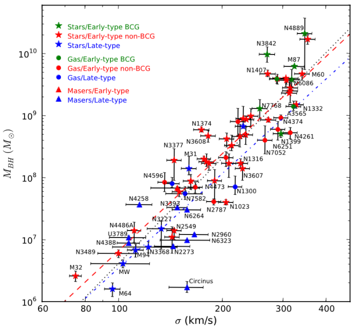
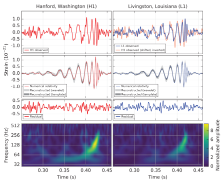


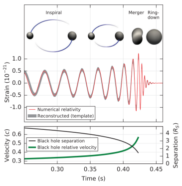
Figure 1. $M_\bullet$–σ relation for our full sample of 72 galaxies listed in Table 3 and at http://blackhole.berkeley.edu. Brightest cluster galaxies (BCGs) that are also the central galaxies of their clusters are plotted in green, other elliptical and S0 galaxies are plotted in red, and late-type spiral galaxies are plotted in blue. NGC 1316 is the most luminous galaxy in the Fornax cluster, but it lies at the cluster outskirts; the green symbol here labels the central galaxy NGC 1399. M87 lies near the center of the Virgo cluster, whereas NGC 4472 (M49) lies ~1 Mpc to the south. The black hole masses are measured using the dynamics of masers (triangles), stars (stars), or gas (circles). Error bars indicate 68% confidence intervals. For most of the maser galaxies, the error bars in $M_\bullet$ are smaller than the plotted symbol. The black dotted line shows the best-fitting power law for the entire sample: $\log_{10}(M_\bullet/M_\odot) = 8.32+5.64\log_{10}(\sigma/200\,\mathrm{km\,s^{-1}})$. When early-type and late-type galaxies are fit separately, the resulting power laws are $\log_{10}(M_\bullet/M_\odot) = 8.39+5.20\log_{10}(\sigma/200\,\mathrm{km\,s^{-1}})$ for the early type (red dashed line), and $\log_{10}(M_\bullet/M_\odot) = 8.07+5.06\log_{10}(\sigma/200\,\mathrm{km\,s^{-1}})$ for the late type (blue dot-dashed line). The plotted values of σ are derived using kinematic data over the radii $r_{\mathrm{inf}} < r < r_{\mathrm{eff}}$.

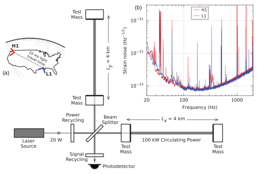
- ▷ SMBHs are found at the center of galaxies
- ▷ The Milky Way harbours a 4.3 $\times 10^6\,M_\odot$BH at its center

---

Fusion of black holes



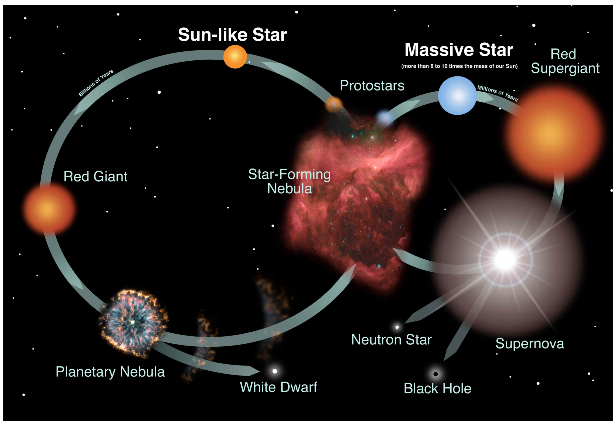




- ▷ Detection of Gravitational waves produced by the fusion of two black holes by the two LIGO observatories (3000 km apart; 7ms-light) detected on 14-sep-2015
  - Power ~ few 10^{49} W at peak (more than all stars in the universe)
  - Measurement of $\Delta L(t) = \delta L_x - \delta L_y = h(t)L_0$, L_0=4km, h(t)=strain
  - Merger: distance: 410 Mpc, z=0.09; mass 36 and 29 $M_\odot$
- ▷ GW150914 (more information here and here)

---

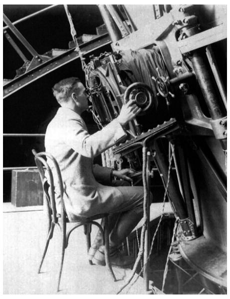
6 The stellar cycle

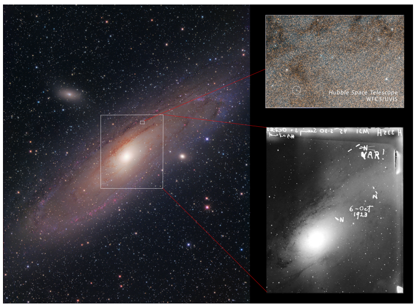


7 The expansion of the Universe

- Galaxies were discovered in the 1920s, opening a new field, that of observational cosmology
- Once galaxies were discovered, their motions relative to us was measured and the expansion of the universe was demonstrated

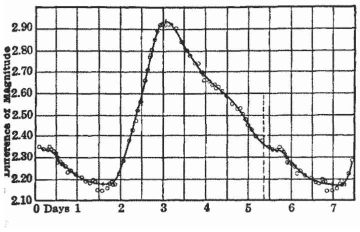
M31: The first extragalactic object

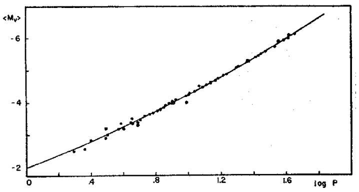




- Using Cepheids, E. Hubble computed the distance to the Andromeda Galaxy (see here)
- His value, 300 kpc (actually a factor two too low) implies that M31 is outside the M-W.
- This was the first proof for the existence of structures outside the Milky Way (see also this link); see Tammann 2005 for historical aspects.

Cepheids

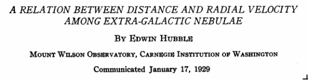




- Left: what we call a *light curve* showing the luminosity as a function of time of the star δ Cephei, (4th magnitude F5 supergiant) P=5.37 d
- Right: the relation between absolute magnitude ($M = -2.5 \log_{10} \mathscr{L} + M_0$) with the Period ($\log_{10}$P) for *25 variable stars in the SMC*, Leavitt & Pickering 1912

measuring the period gives the luminosity, and therefore, the distance!

The Hubble law


A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

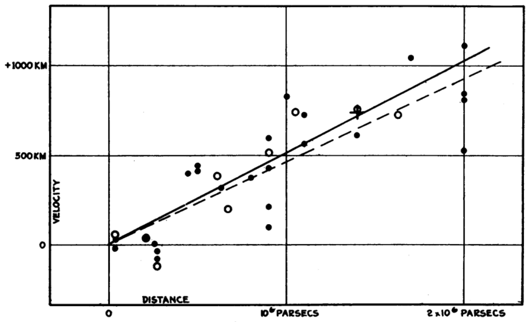


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

The Hubble's constant

- The Universe is expanding. Locally, the Hubble's law (1929, see here) says that any two objects move away (after subtracting their peculiar motions) from each other at a velocity which increases in proportion to the *distance* between them.
- The Hubble's constant H_0 is the *present* value of the expansion rate of the Universe, *H(t)*
- Cosmological distances are primarily expressed as *redshift*

$$\lambda_{\rm obs} = (1+z)\lambda_0$$

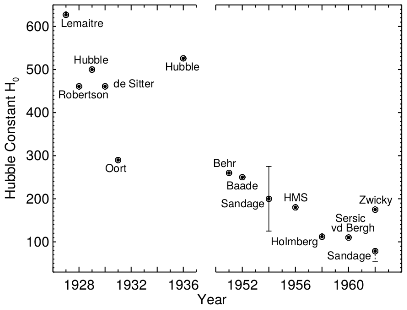
$$z = (\lambda_{\rm obs} - \lambda_0)/\lambda_0$$

- For small z, H_0 relates the recession velocity *v* to the distance d

$$v = cz = H_0 d$$

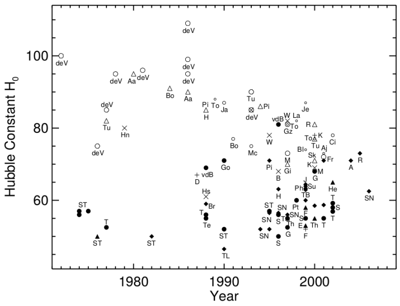
- How is H_0 determined ? You need to know the redshift (now, easy) and a *distance*. The latter is the challenging part of the game. **Distances are determined using stars: the better we understand stars, the better we measure the Universe.**

The challenge of measuring H_0



- The evolution of the value of H_0 in the early times, illustrating the difficulty of the measurement: from 550 (Hubble 1929) to 55 (Sandage 1962) !
- Difficulty: distance determination were underestimated by factors 5-10
  - incorrect interpretation of the magnitudes
  - calibration of the P-L relation of Cepheids

The current picture



- ▹ Use different distance measurement tools: variables stars (Cepheids, RR Lyrae), Supernova, Tully-Fisher empirical law, etc. . .
- ▹ Most accurate: Cepheids, SNIa; currently: SNIa at z up to 2.3

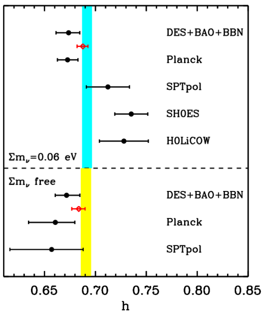
Current value: noted $\mathbf{H_0}$, ≈ 70 km/s/Mpc, or z=2.4(-4) d_{Mpc} or $d_{\mathrm{Mpc}} \approx 4200$ z

---

Accelerating expansion

- ▹ The Hubble Space Telescope: measure the expansion rate and geometry of the Universe
- ▹ Observe Cepheids and SNIa at large distances (up to z≈ 0.5)
- ▹ Result: expansion will last forever and is currently accelerating
- ▹ Nobel Prize 2011: Perlmutter, Riess, and Schmidt

A crack in the standard cosmological model?



- ▹ CMB measurements (Planck mission): (flat Λ CDM): H_0 = 67.3±1.0 km/s/Mpc
- ▹ SNIa and Cepheid method (Riess et al 2018) H_0 = 73.52±1.62 km/s/Mpc
- ▹ Baryon Acoustic Oscillations (Abbott et al 2018): (flat Λ CDM) H_0=67.4±1.2 km/s/Mpc
- ▹ At the root of the discrepancy: the compelling accuracy of distance determination with *Cepheids*;