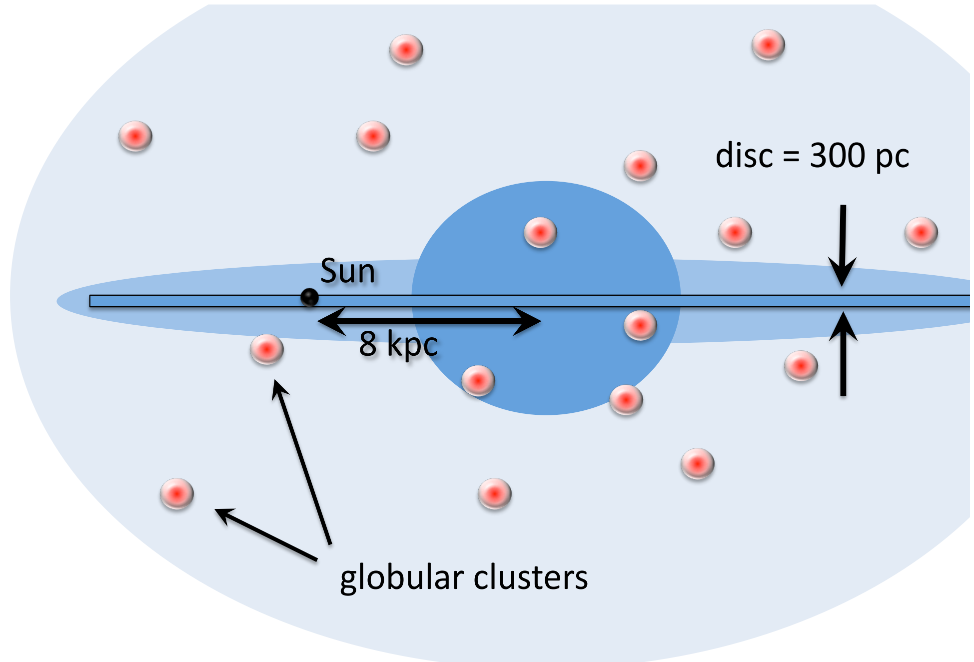
1 - Stars: Introduction

The Milky Way

- Is a spiral galaxy, about 50 kpc across and about 1 kpc thick
    - 1 parsec is **3.1×10^{16} m**, or **3.26 light years** (ly).
    - Distance between the Earth and the Sun is called the Astronomical Unit, **1 AU = 1.5×10^{13} cm**.

- Disk has a diameter of about 50 kpc, is about 300 pc thick, mostly filled with interstellar dust and gas.

- Is part of **Local Group**, a cluster of some 20 galaxies which include the Large Magellanic Cloud, our nearest galaxy, 50 kpc away, away, and the Andromeda galaxy, 650 kpc away.



- The Local Group is part of the larger **Virgo supercluster**.

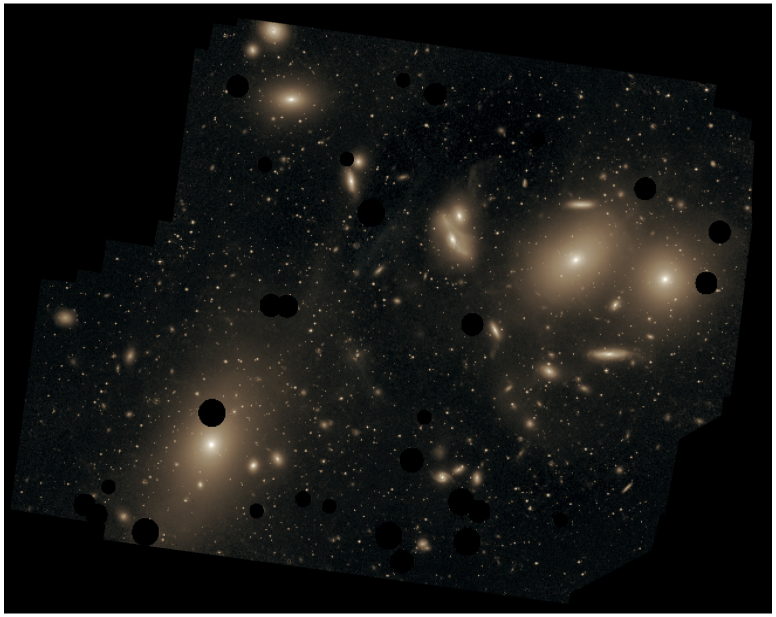
- The visible Universe contains some 10^{11} galaxies.

The Milky Way

- The **mass of our Sun** is 1.99×10^{30} kg = 1 solar mass, $M_\odot$
- The **mass of the Milky Way** is larger than 2×10^{11} $M_\odot$

  - 10% of the mass is interstellar gas
  - 0.1% is dust (typically particles with diameter 0.01 - 0.1 μm)
  - interstellar gas density varies from about 10^9 (in dark clouds) to 10^5 atoms m^{-3} (on the average ~ 1 atom cm^{-3}).
  - Mainly H and He. Large and rather complex molecules containing H, C (up to C_{70} molecules), N and O (including amino acids) have also been discovered.

The Large Magellanic Cloud.

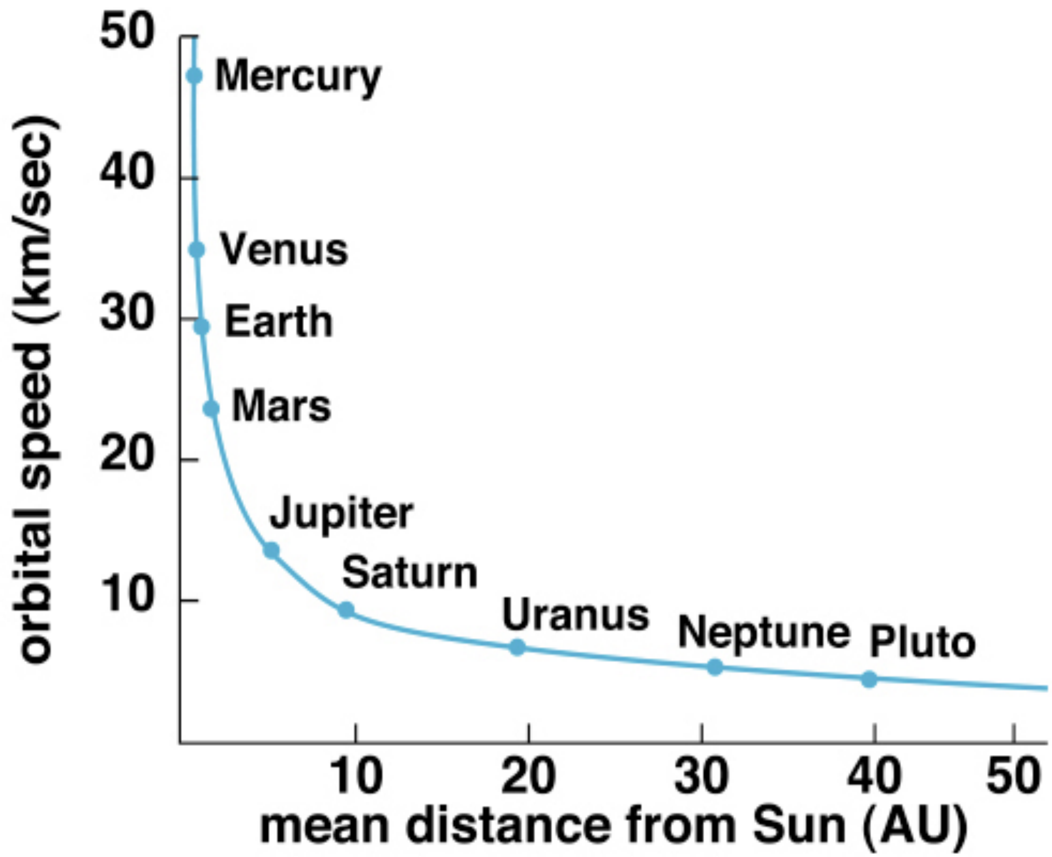


Deep image of the Virgo Cluster.

1.2 - Dark Matter

A **rotation curve** is a graph of how fast something is rotating as a function of distance from the center.

Here is the rotation curve of our solar system. The farther from Sun, the slower planets are rotating.



A rotation curve is used to measure the **mass** inside.

But astronomers have been found many galaxies with **flat rotation curves**, including the Milky Way.

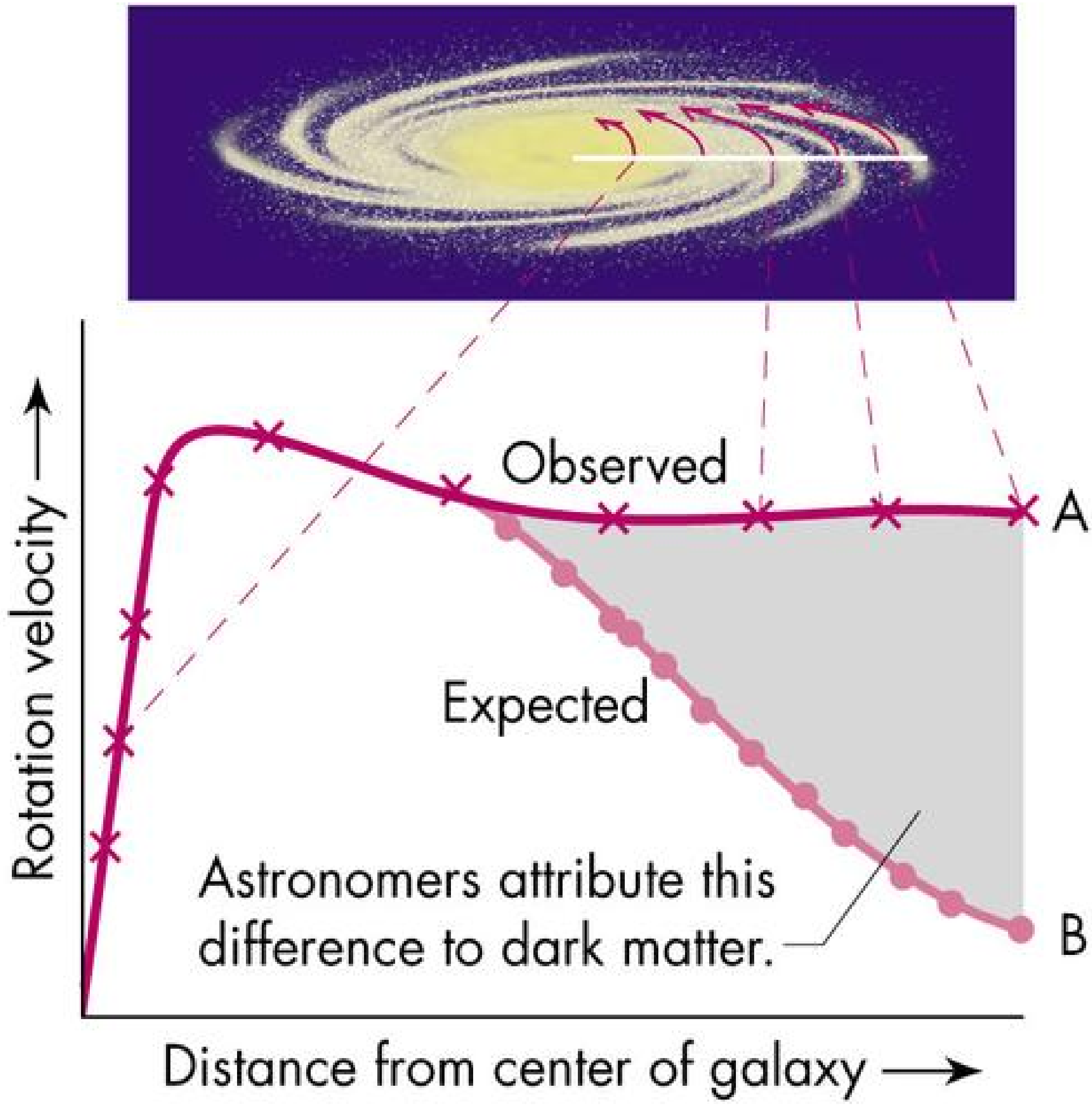
Flat rotation curves

The rotation curves show that mass in a galaxy is not concentrated in the center, but is distributed throughout the galaxy

But most of this mass cannot be seen; it gives off no light.

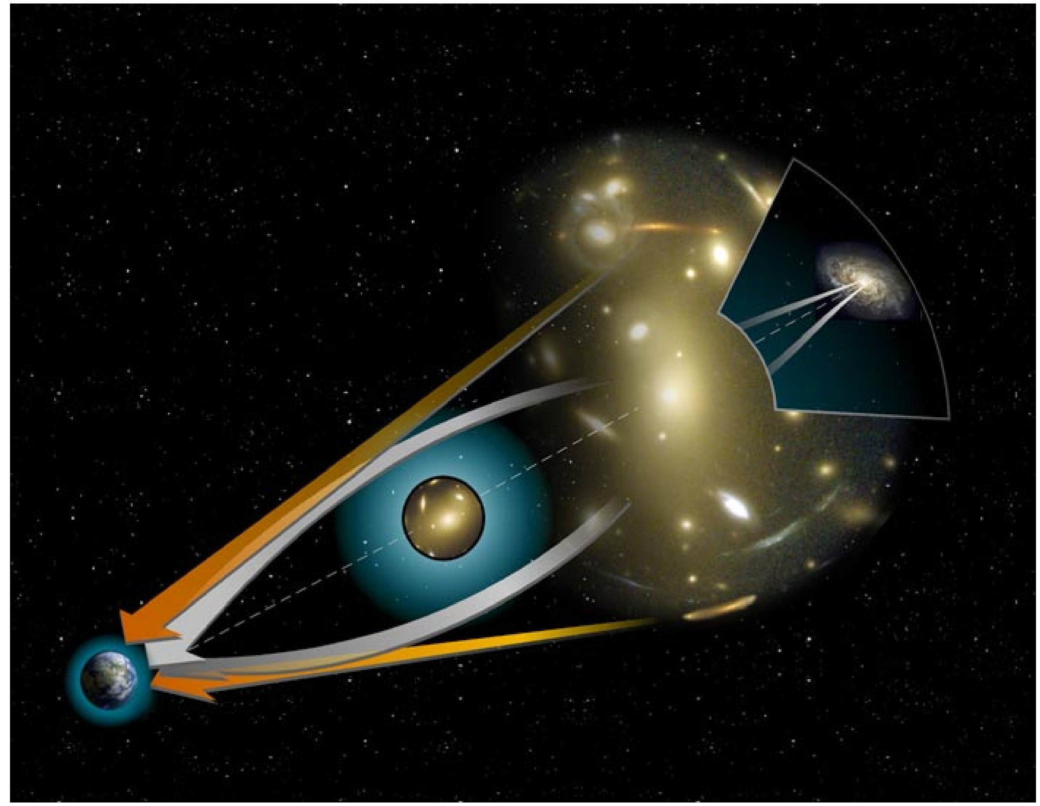
Observations show that up to 90% of the mass of the universe is **dark** (invisible) **matter**!

The dark matter is probably distributed throughout the galaxy **halo**.

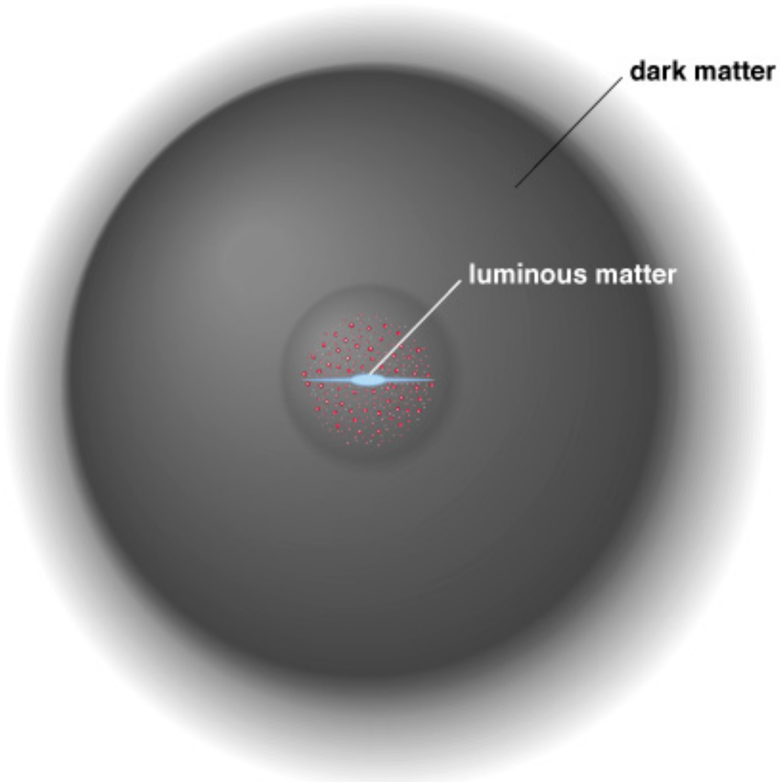


Gravitational Lensing

Light passing by a massive object will bend, as for example, starlight near the Sun.



The image of a light source is distorted into a ring or an arc. The amount of bending is proportional to the mass of the object.



Gravitational lensing observations reveal the amount of mass in a galaxy.

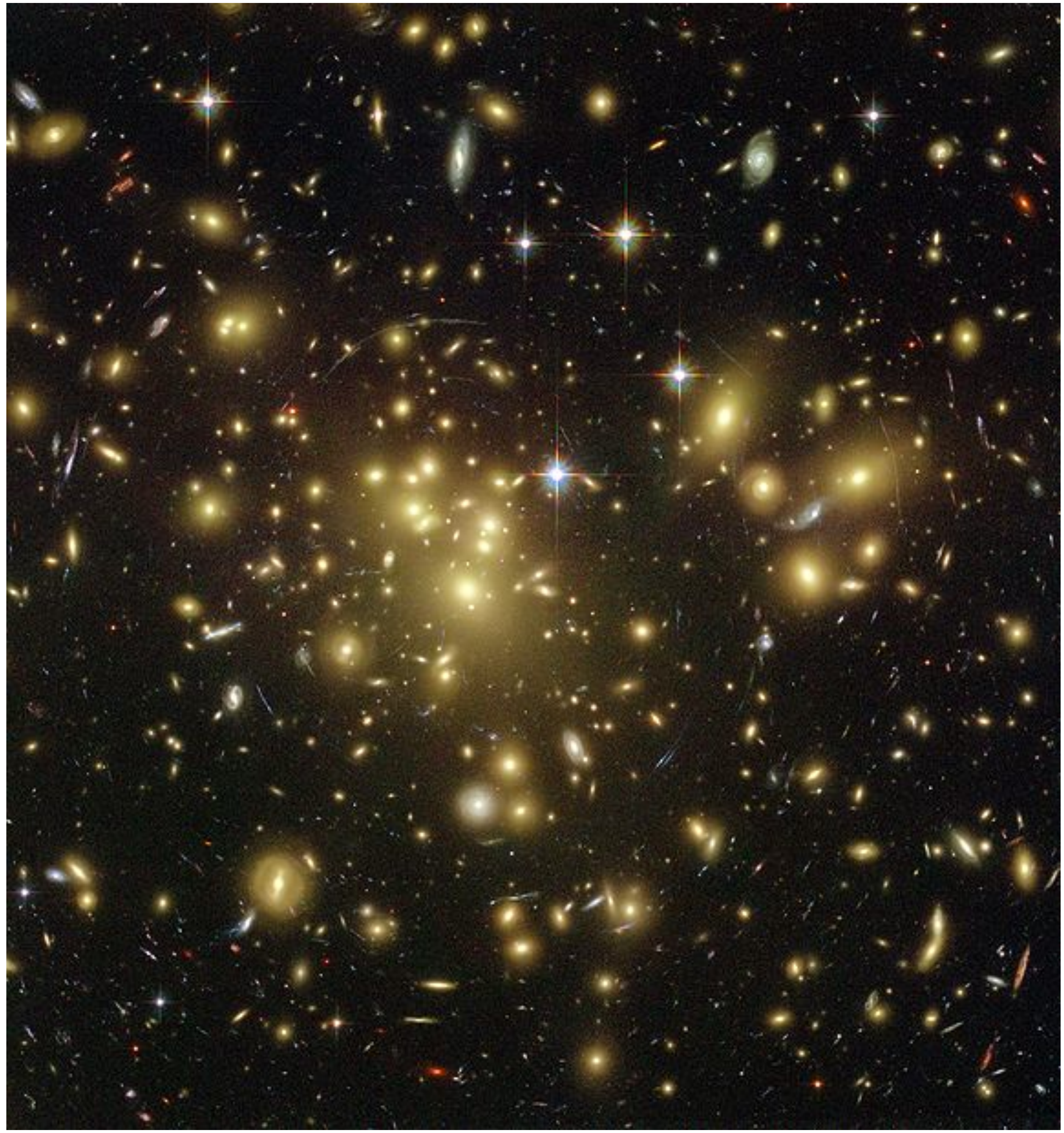
Observation of exceptionally large gravitational lensing is a further proof that galaxies contain a large amount of **dark matter**.

Gravitational Lensing

Gravitational lensing has been observed by the Hubble Space Telescope, as seen in this picture.

Lensing arcs are clearly visible. They are indicative of the presence of dark matter.

The picture is from the **galaxy cluster Abell 2029**, composed of thousands of galaxies enveloped in a cloud of hot gas.



1.3 - Black Holes

Escape velocity:

Consider the **kinetic energy K and gravitational potential energy U** of a body close to a star of mass M. Conservation of energy implies

$$(K+U)_i = (K+U)_f \qquad (1.1)$$

The body escapes the gravitational pull of the star if it can reach infinity (*$U_f = 0$*). Then K_f = 0 because final velocity is zero and from Newton's gravitational law

$$\frac{1}{2}mv_e^2 - G\frac{mM}{R} = 0 \qquad (1.2)$$

where R is the initial distance between m and M. From this we get the **escape velocity**

$$v_e = \sqrt{\frac{2MG}{R}} \qquad (1.3)$$

G is the universal gravitational constant (G = 6.67×10^{-11} m^3 kg^{-1} s^{-2})

Examples: (a) Earth's mass (5.94×10^{24} kg), R = 6,400 km → v_e = 11 km/s
(b) object with $M_\odot$ and R = 3 km → $v_e > 3 \times 10^8$ km/s (*larger than speed of light*) → **black-hole**

1.4 - Typical Stars: Young stars

Dwarfs

Small stars, < 20 $M_\odot$ and luminosity L < 20,000 $L_\odot$. Our sun is a dwarf star.

Yellow dwarfs

Small, main sequence stars. The Sun is a yellow dwarf.

Red dwarf

Small, cool, very faint, main sequence star. Surface temperature < 4,000 K. Red dwarfs are the most common type of star. Proxima Centauri is a red dwarf.

***Proxima Centauri**:*
~ 4.24 ly away, in the constellation of Centaurus.

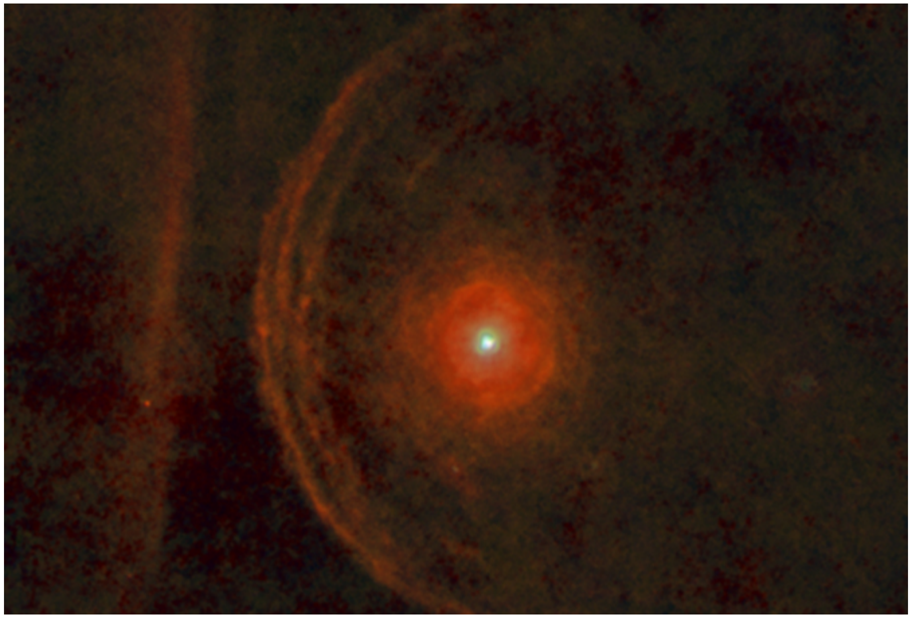
Old, Large Stars

Red giant
Radius about 100 times bigger than it was originally, and had become cooler (surface temperature < 6,500 K). They are frequently orange in color. **Betelgeuse** is a red giant.

Blue giant
Huge, very hot, blue star. It is a post-main sequence star that burns helium.

Supergiant
Largest known type of star – can be as large as our entire solar system. **Betelgeuse** and **Rigel** are supergiants. Rare. Supergiants die as supernova and become black holes.

Betelgeuse:
20 $M_\odot$
520 ly away
1 Billion km diameter
7,500 brighter than the Sun
Surface Temperature: 6000 K

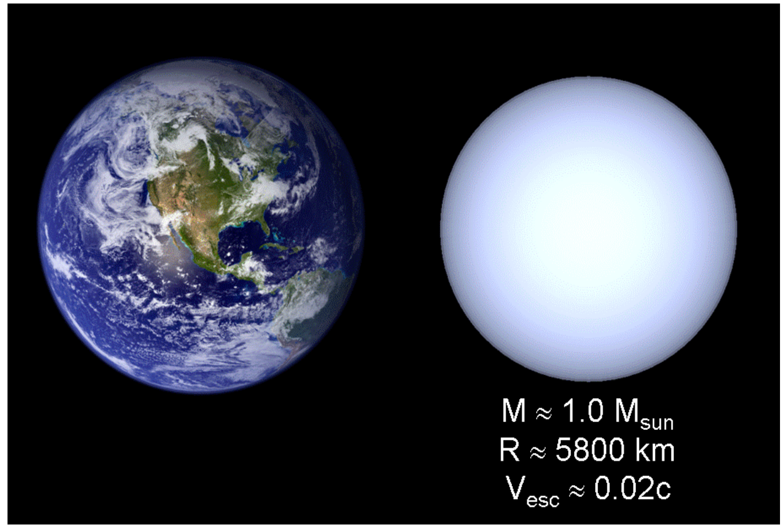


Faint Stars

White dwarf

Small, very dense, hot, made mostly of carbon. Remains after a red giant star loses its outer layers. Their nuclear cores are depleted (i.e., no more nuclear reactions).

R_{WD} ~ R_{Earth} but $M_{DW} >> M_{Earth}$
Sirius is a white dwarf.



Typical white dwarf

Brown dwarf

Mass is too small -- no nuclear fusion in its core -- not very luminous. Mass smaller than ~ 80 M_J (M_J = Jupiter mass).

Neutron star

Very small, super-dense, composed mostly of tightly-packed neutrons -- has a thin atmosphere of hydrogen -- radius ~ 5-16 km – density ~ 10^{15} gm/cm^3.

Pulsar

Rapidly spinning neutron star that emits energy in pulses.

Binary Stars

Two stars rotating around their center of mass. About half of all stars are in binary systems.

Polaris (the pole star of the Northern Hemisphere of Earth) is part of a binary star system.

Eclipsing binary

Two close stars appearing to be a single star varying in brightness. The variation in brightness is due to the stars periodically obscuring or enhancing one another.

X-ray binary star

One of the stars is a collapsed object such as a white dwarf, neutron star, or black hole. Matter is stripped from the normal star, falling into the collapsed star, and producing X-rays.

Eclipsing binary star system. (Animation credit: European Southern Observatory.)

Variable Stars

Stars with variable luminosity

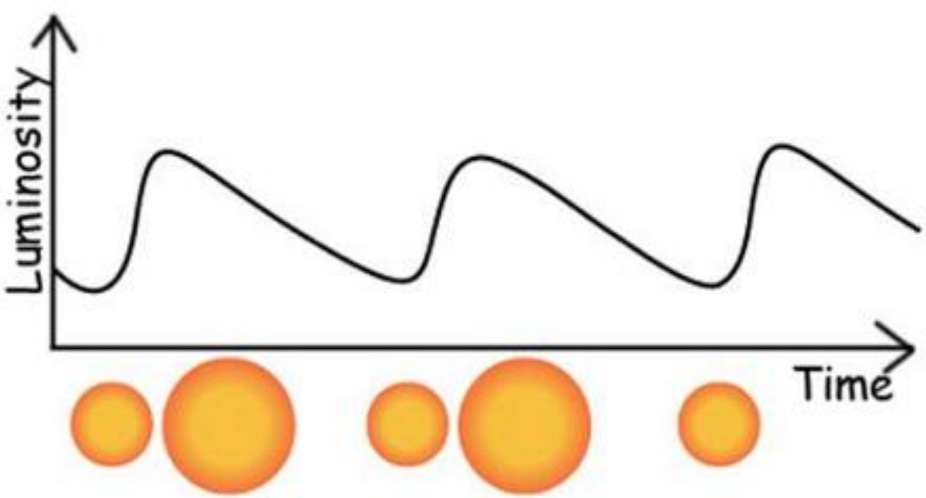
Cepheid variable stars

Regularly pulsate in size and change in brightness. As the star increases in size, its brightness decreases; then, the reverse occurs.
Polaris and **Delta Cephei** are Cepheids.

Mira variable stars

Brightness and size cycle over a very long time period, in the order of many months. Miras are pulsating red giants.

Typical light curve for a Cepheid variable star.



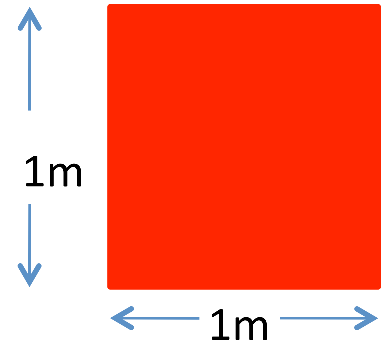
Yerkes spectral classification

TYPE	Star
Ia	Very luminous supergiants
Ib	Less luminous supergiants
II	Luminous giants
III	Giants
IV	Subgiants
V	Main sequence stars (dwarf stars)
VI	Subdwarf
VII	White Dwarf

1.5 - Luminosity and brightness

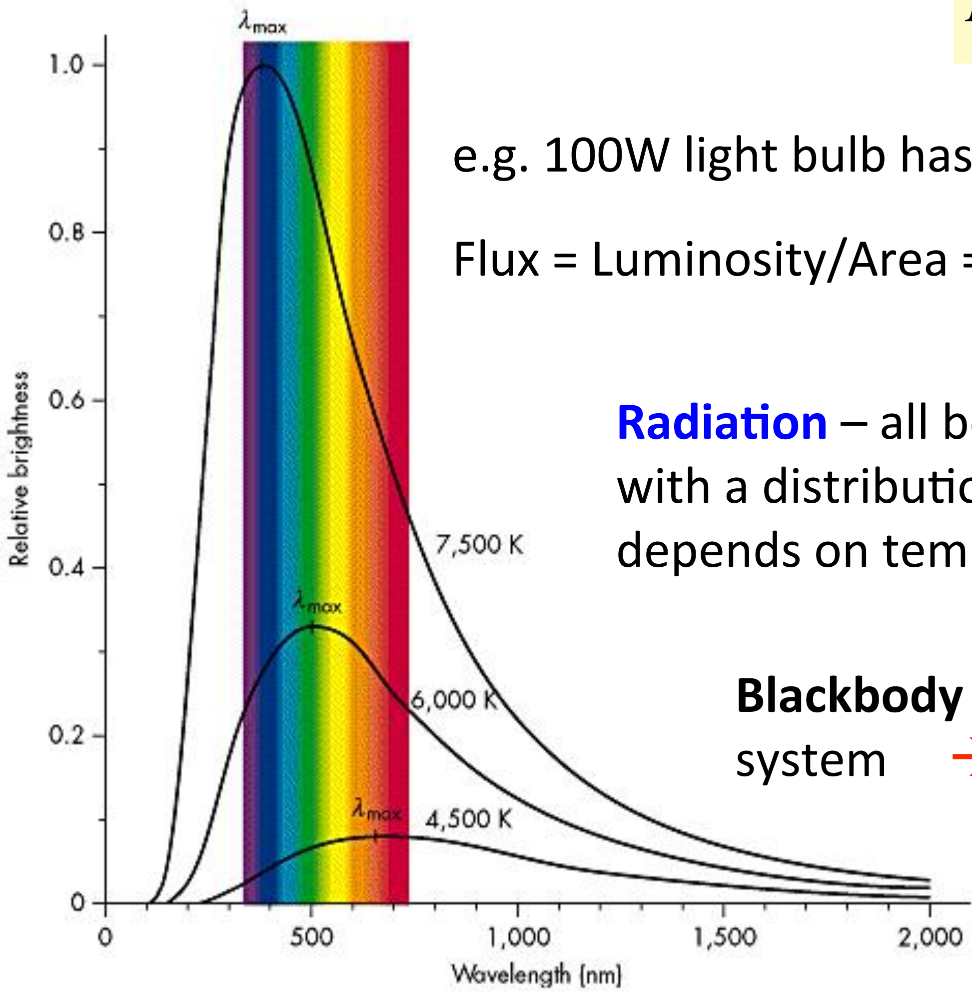
Flux: the total light energy emitted by one square meter of an object every second

$$F \ (\mathrm{J/m^2/s = W/m^2}) \quad (1.4)$$



Luminosity: the total light energy emitted by the whole surface area of an object every second

$$L = \left(\mathrm{Area} \times F\right) \ (\mathrm{J/s}) \quad (1.5)$$



e.g. 100W light bulb has a surface area of about 0.01 m^2

Flux = Luminosity/Area = 100 / 0.01 = 10,000 W/ m^2

Radiation – all bodies radiate EM waves at all wavelengths with a distribution of energy over the wavelengths that depends on temperature T

Blackbody radiation: photons are in equilibrium with the system → **Stefan-Boltzmann law**:

$$F = \sigma T^4 \quad (1.6)$$

Temperature

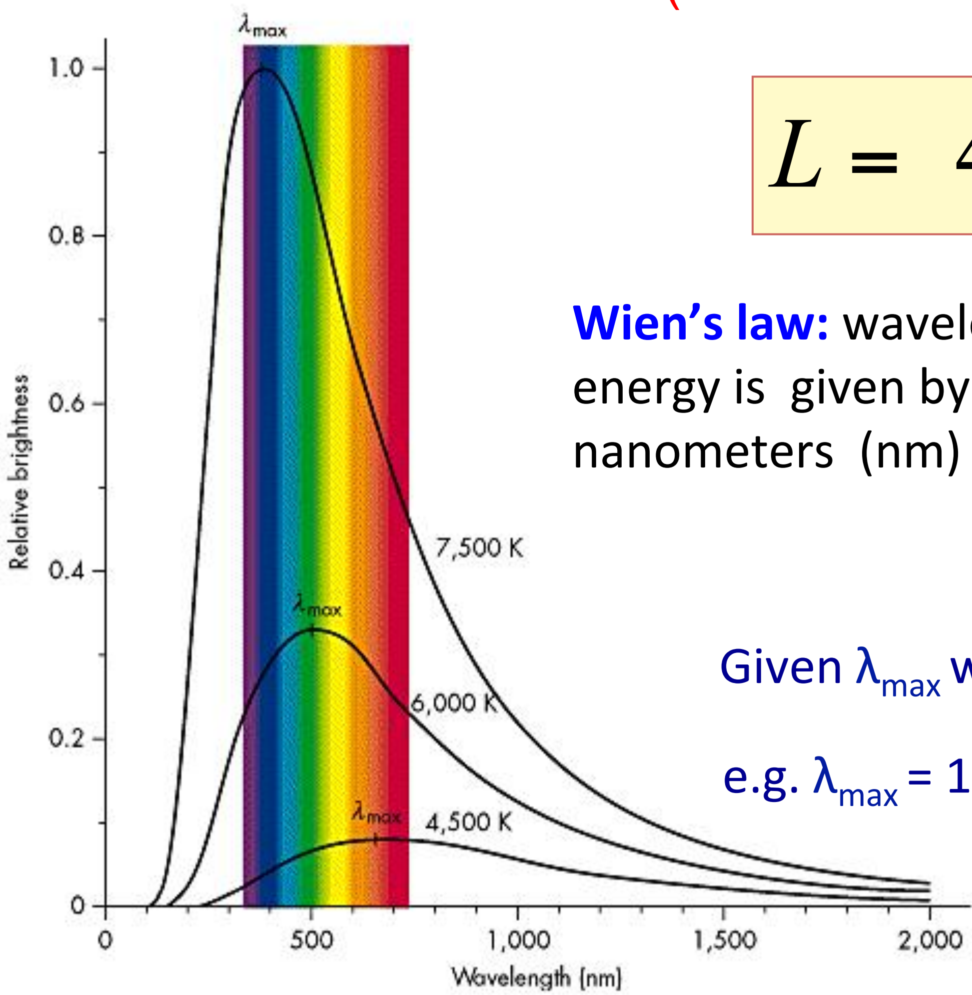
Total luminosity: integral over all wavelengths

$$L = \int_0^\infty L_\lambda d\lambda \qquad (1.7)$$

Effective temperature (T_e):
The temperature of a black body of the same radius as the star that would radiate the same amount of energy. Thus, from Stefan-Boltzmann law

σ = (**5.67× 10^{-8} W m^{-2} K^{-4}**)

$$L = 4\pi R^2 \sigma T_e^4 \qquad (1.8)$$



Wien's law: wavelength at which blackbody radiates most of its energy is given by **λ_{max} = 3,000,000/T** as long λ_{max} is measured in nanometers (nm) (1nm = 10^{-9}m = 0.000000001m)

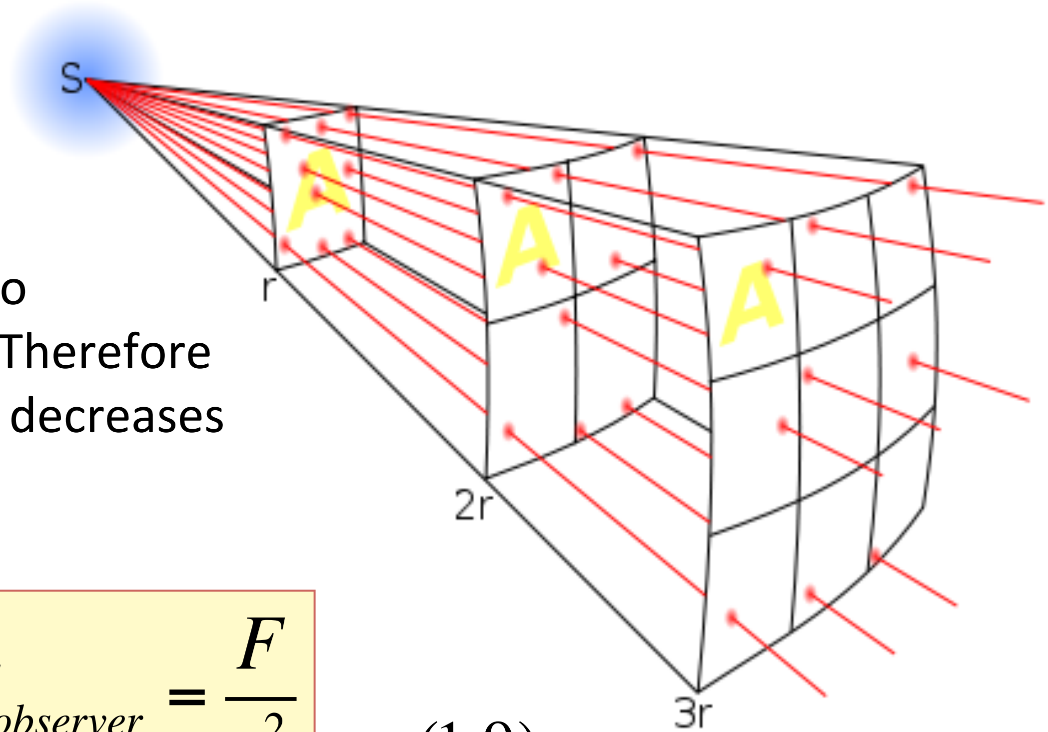
Given λ_{max} we can calculate T from T = 3,000,000/ λ_{max}

e.g. λ_{max} = 1000 nm gives T = 3,000,000/1000 = 3,000 K

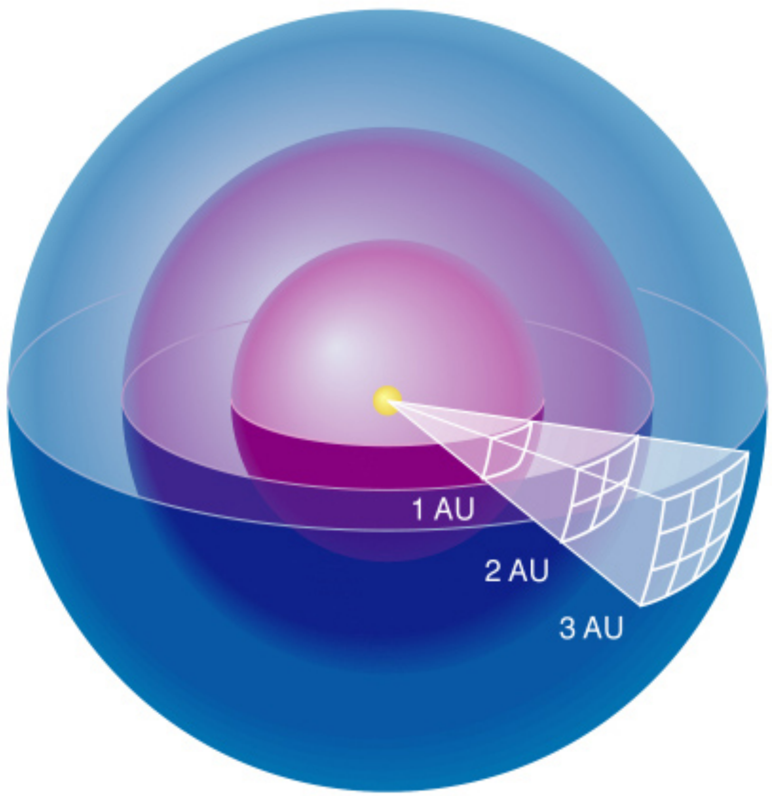
Brightness

Inverse square law:

Increase the size of a sphere from radius r
To radius 2r → Area increases from $4\pi r^2$ to $4\pi(2r)^2 = 16\,\pi r^2$, i.e., by a factor of $2^2 = 4$. Therefore flux (light energy per second per unit area) decreases by a factor of $2^2 = 4$.



$$F_{observer} = \frac{F}{r^2} \qquad (1.9)$$



1 AU = Astronomical Unit = distance Sun-Earth

10 million dollars question: Assume two stars that look to have same brightness.

- Are they at the same distance from our solar system?
- Or do they have different brightness, with the more bright star farther from our solar system than the less bright star?

Apparent magnitude m_v (how bright stars appear)

- Origins with **Hipparchus** (120 BC) and **Ptolemy** (150 AD)

Magnitude is a **logarithmic measure of luminosity** with the brightest stars having the lowest magnitude.

Stars are classified by giving a number 1 - 6

- Brightest stars are **class 1**
- Dimmest stars visible to naked eye are **class 6**
- Class 1 is twice as bright as class 2, class 2 is twice as bright as class 3, and so on.
- Therefore, class 1 is $2^6 = 64$ times as bright as class 6

Modified in the 19th Century

- Modern scale is defined so that 6th magnitude stars are exactly 100 times brighter than 1st magnitude stars
- → stars that differ in magnitude by 1 differ by a factor of 2.512 (e.g. a **3rd magnitude** star is 2.512 times brighter than a **2nd magnitude** star): $(2.512)^5 = 100$

Modern definions: Apparent & absolute magnitudes

The historical classification of stars into brightness classes is called **visual**, or apparent magnitude, $\mathbf{m_v}$, or simply $\mathbf{m}$. It refers to the amount of radiation which falls on unit area of a detector on the Earth's surface.

The absolute magnitude, **M**, is a measure of the real star's luminosity (or brightness). It is also defined so that a difference of 5 magnitudes corresponds to a factor of exactly 100 times in intensity. In this scale, the Sun has M = +5.

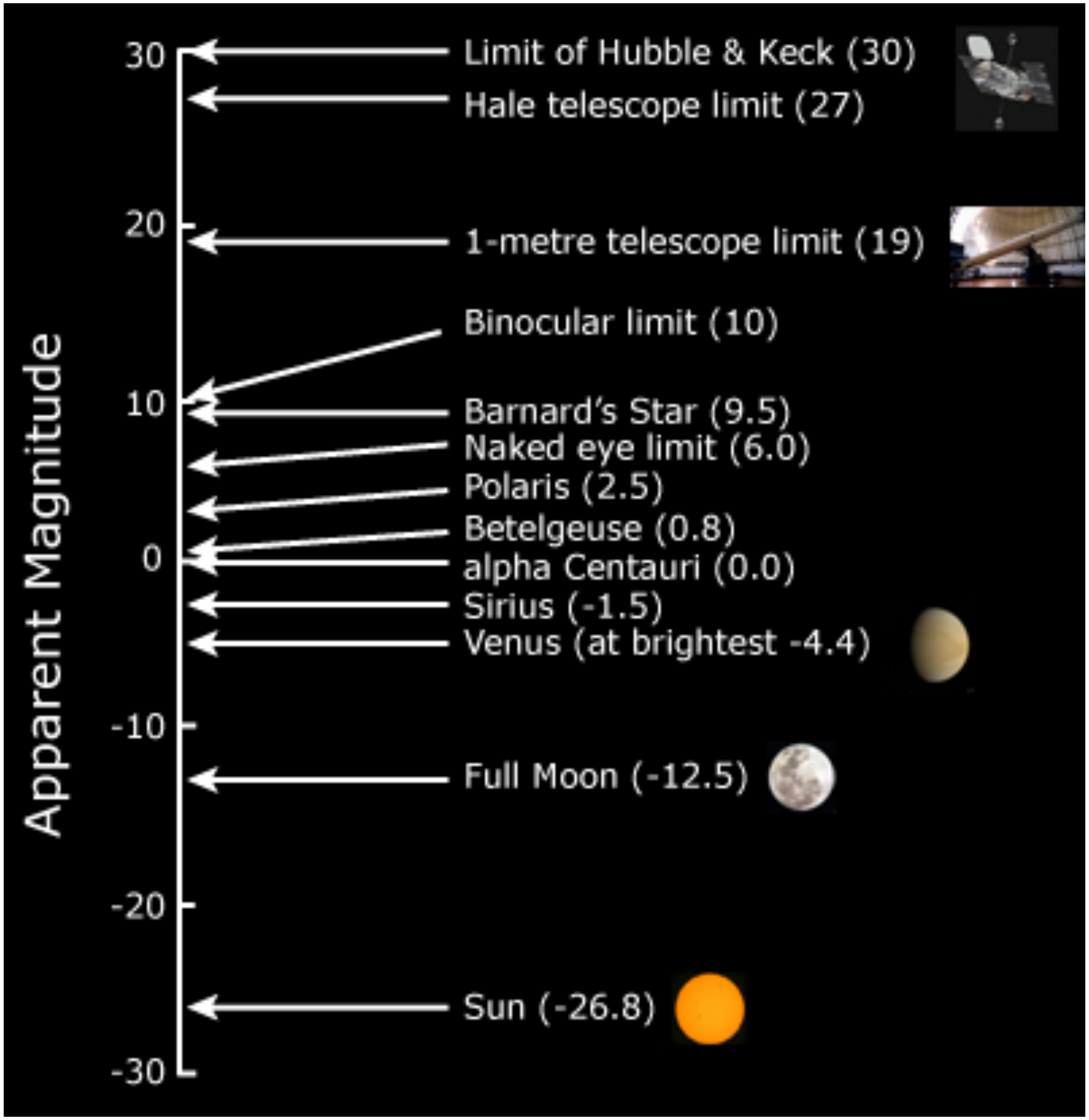
The apparent magnitude is defined so that if the star is at 10 parsecs (or 32.6 ly) distance from us, then its apparent magnitude is equal to its absolute magnitude. The magnitudes m_1 and m_2 for two stars with corresponding apparent luminosities F_1 and F_2 are related by

$$\boxed{m_2 - m_1 = 2.5 \log \frac{F_1}{F_2}} \qquad (1.10)$$

→ reasonable agreement with the historical estimates because **the human eye most closely responds to the logarithm of the luminosity** than to the luminosity itself.

Examples: **(a)** m = - 1.5 for Sirius (brightest star), **(b)** m = - 26.8 for the Sun, and **(c)** m = 25 for the faintest object visible from Earth telescopes.

Apparent magnitude m (how bright stars appear)



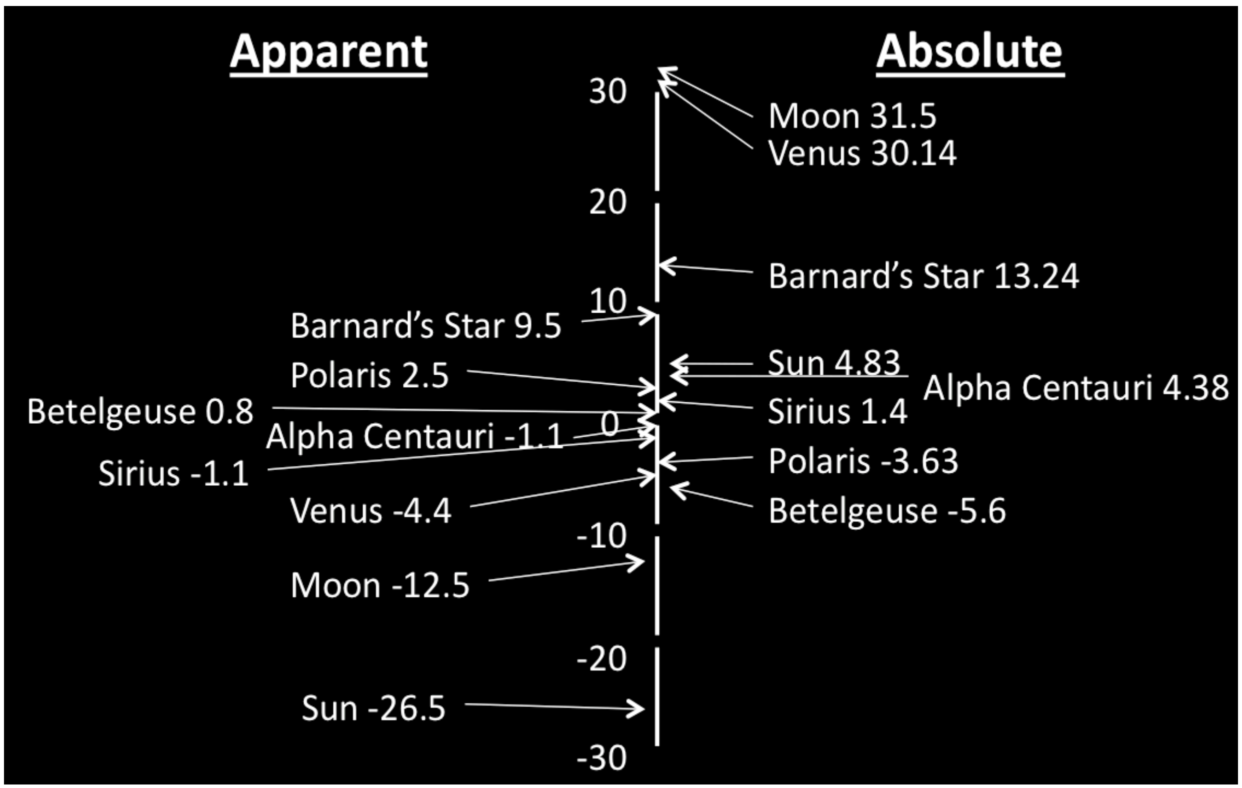
Credit: ESA (European Space Agency)

Absolute magnitude M (How bright stars would appear if they were all the same distance away)

- **Absolute Magnitude** M defined as apparent magnitude of a star if it were placed at a distance of 10 pc (M is a theoretical quantity)
- Ranges from -8 for the most energetic star to 15 for less energetic.

$$m - M = 5\log(d/10) \qquad (1.11)$$

where *d* is in pc.



m – M	d (pc)
0	10
1	16
2	25
3	40
4	63
5	100
6	160
7	250
8	400
9	630
10	1000
15	10,000
20	100,000

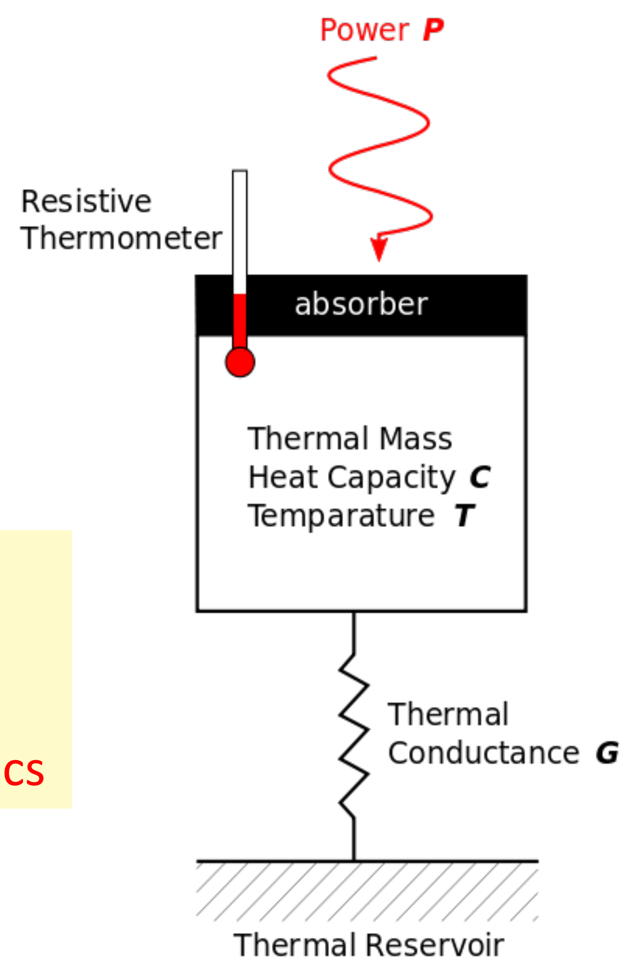
m-M is known as the **distance modulus** and can be used to determine the distance to an object.

1.5 - Distance to stars: Bolometric magnitude M_{bol}

Magnitudes are measured in some wavelength band. To compare with theory it is more useful to determine **bolometric magnitude** – defined as absolute magnitude that would be measured by a bolometer* sensitive to all wavelengths. The difference in bolometric magnitude is related to the luminosity ratio according to:

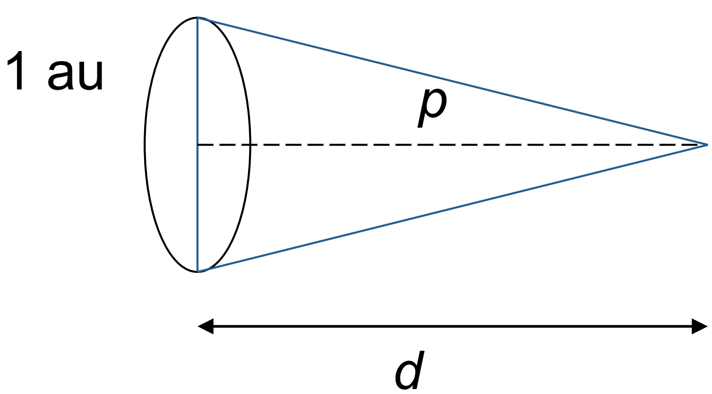
* A bolometer measures the power of incident electromagnetic radiation via the heating of a material.

$$M_{bol}^{star} - M_{bol}^{Sun} = -2.5 \log \frac{L}{L_{Sun}} \qquad (1.12)$$



Parallax

Can determine distance if we measure ***parallax*** - apparent stellar motion to orbit of earth around Sun.



For small angles

$p = 1\ \mathrm{au}/d$

$d = 1/p$ (parsecs)

If p is measured in arcsecs

$$(1.13)$$

Limits of parallax method

Measured **energy flux** depends on distance to star (inverse square law)

Hence if d is known then L determined

$$\boxed{F = L/4\pi d^2} \qquad (1.14)$$

- Since nearest stars $d > 1$ pc → must measure $p < 1$ arcsec, e.g., at $d = 100$ pc, $p = 0.01$ arcsec **(notation: sec = ‘, arcsec = “)**
- Telescopes on ground have resolution ~1” – **Hubble telescope** has resolution 0.05” → **measure by parallax is difficult!**
- **Hipparcos satellite** measured 10^5 bright stars with $\delta p \sim 0.001''$ $\Rightarrow$ confident distances for stars with $d < 100$ pc
- Hence ~ 100 stars with well measured parallax distances

Stellar radius: Angular diameter of Sun at distance of 10 pc:
$\theta = 2R_{\odot}/10\ \mathrm{pc} = 5 \times 10^{-9}$ radians $= 10^{-3}$ arcsec

Compare with Hubble resolution of ~ 0.05 arcsec → **very difficult to measure *R* of stars directly**.