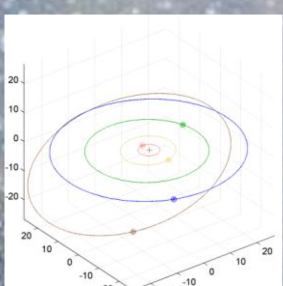
Cosmology

- **Age of the Universe**
  - Future?
  - The cosmic calendar
  - Age of the Earth
  - Red shift
- **Structure and evolution of stars**
- **Relativity**
  - Special Relativity
  - Ideas of General Relativity
    - Gravitational lensing
    - Precession of Mercury
- **Size of the Universe**
  - Measurement
    - Parallax
    - Luminosity
  - Earth
    Solar System
    Galaxy ...
- **Exotic case studies**
  - Neutron stars
  - Black holes, quasars
- **Gravity**
  - Newton/Kepler
  - Einstein
  - Computer Simulation



- **A human history of cosmology**

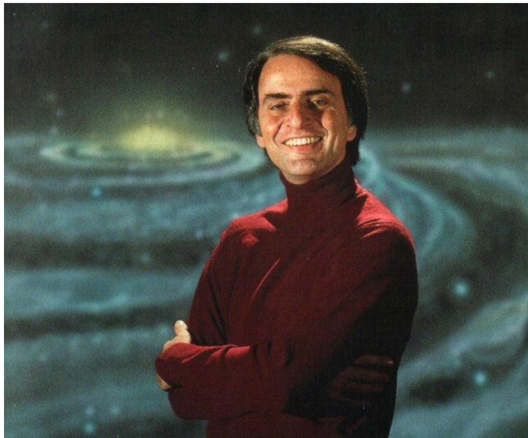
- **Planets & moons**
  - Detecting planets orbiting other stars
  - The Solar System
    - The Earth

The Cosmos is all that is or ever was or ever will be.

In the last few millennia we have made the most astonishing and unexpected discoveries about the Cosmos and our place within it, explorations that are exhilarating to consider. They remind us that humans have evolved to wonder, that understanding is a joy, that knowledge is prerequisite to survival.

I believe our future depends on how well we know this Cosmos in which we float like a mote of dust in the morning sky.

Carl Sagan (1934-1996)
Cosmos pp20

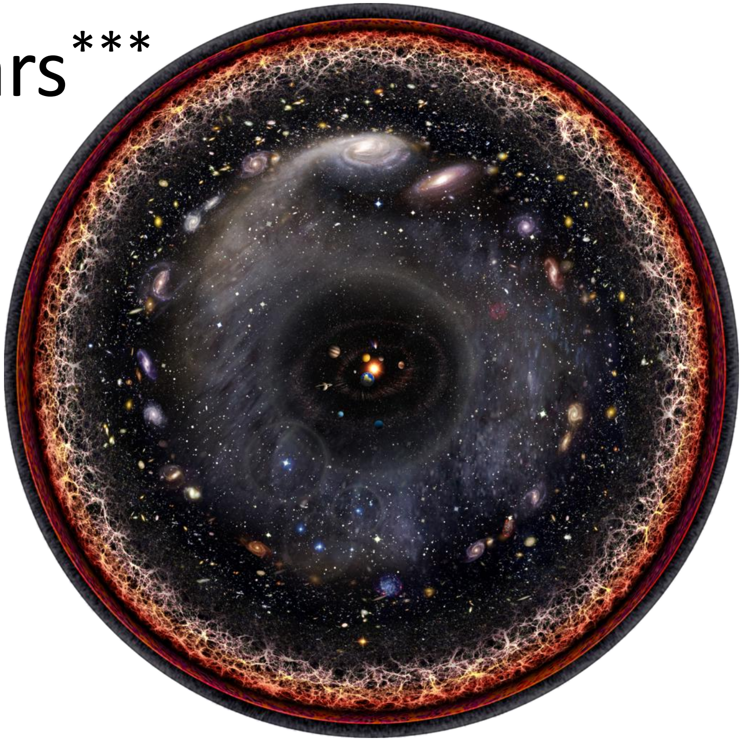


How big is the Universe?
How far away are the stars?
How can we measure these things?

Physical stats of the Universe

Diameter:	93 billion light years
Volume:	4×10^{83} litres
Mass:	10^{53} kg*
Density:	$9.9 \times 10^{-30}\ gcm^{-3}$ **
Age:	13.8 billion years***
Temperature:	2.73K

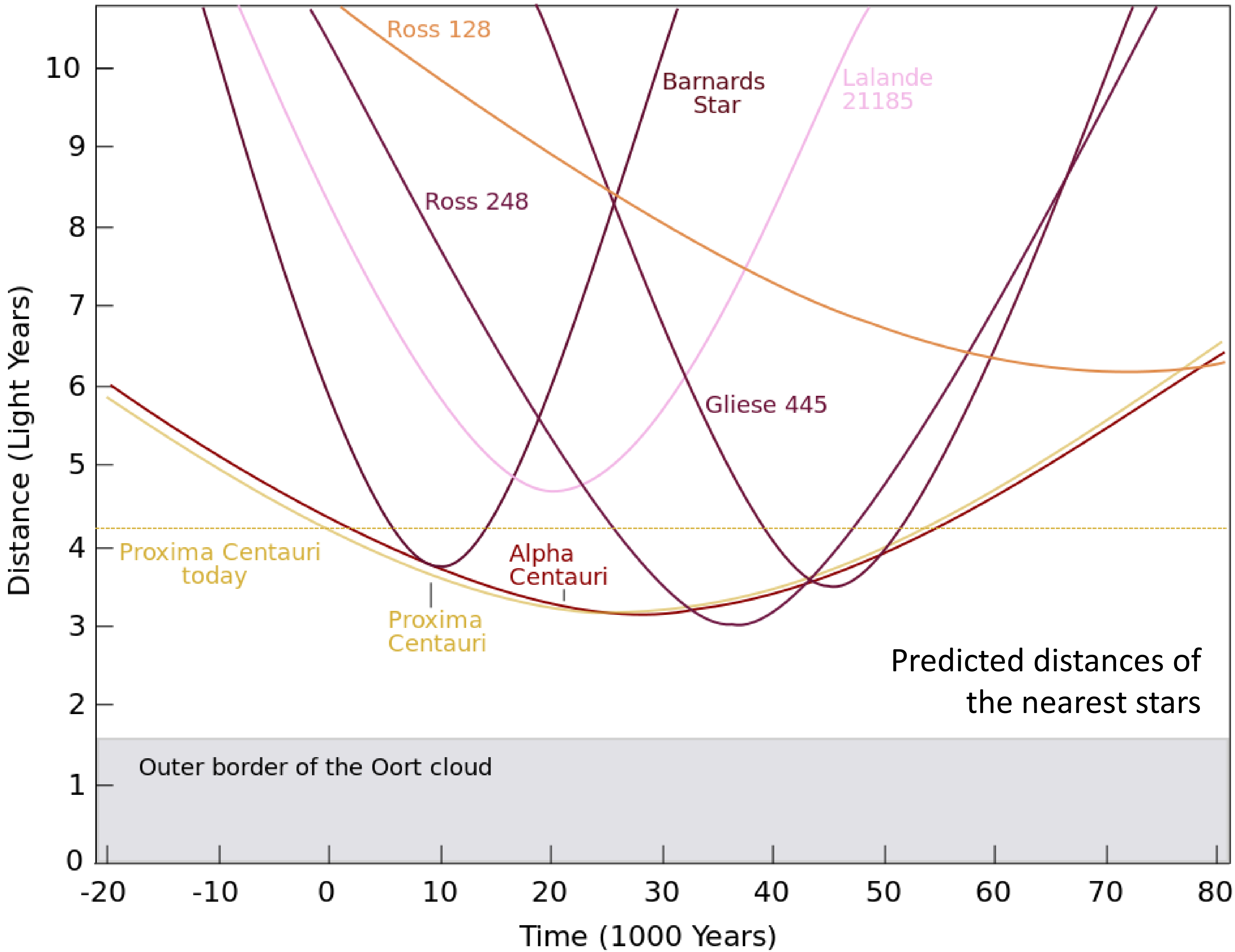
*Ordinary matter:	4.9%
Dark matter:	26.8%
Dark energy:	68.3%



*6 protons per cubic metre

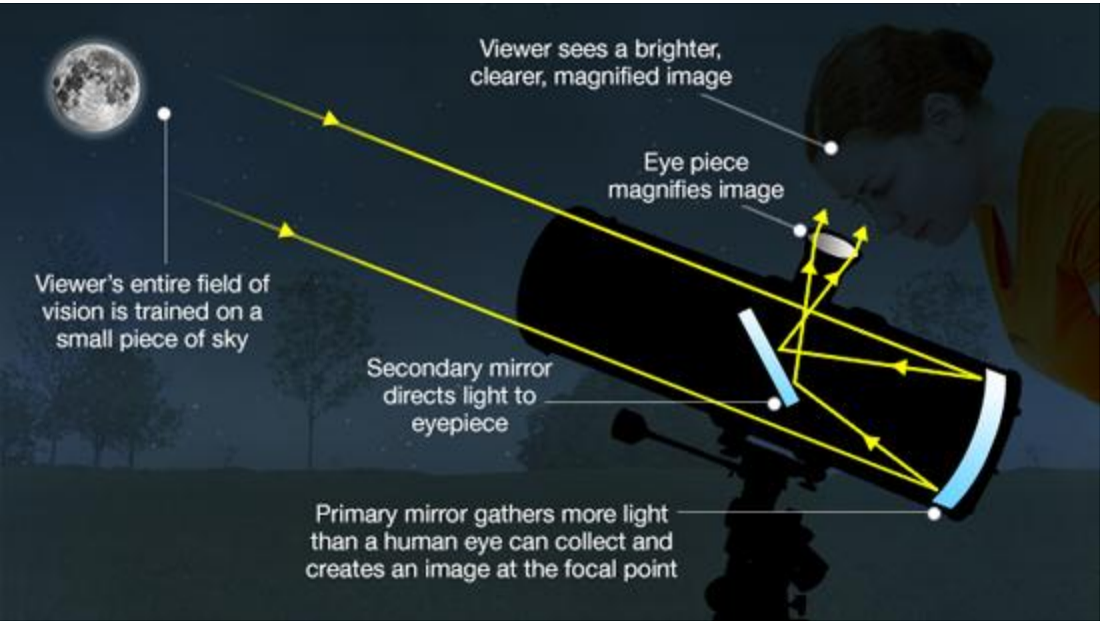
*** The Earth is 4.54 ± 0.05 billion years old

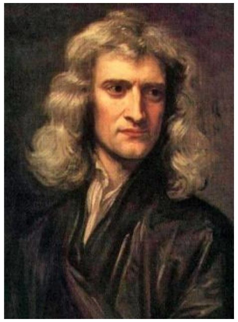
http://en.wikipedia.org/wiki/Observable_universe


Ross 128
Barnards Star
Lalande 21185
Ross 248
Gliese 445
Proxima Centauri today
Alpha Centauri
Proxima Centauri
Predicted distances of the nearest stars
Outer border of the Oort cloud
Distance (Light Years)
Time (1000 Years)
0
1
2
3
4
5
6
7
8
9
10
-20
-10
0
10
20
30
40
50
60
70
80

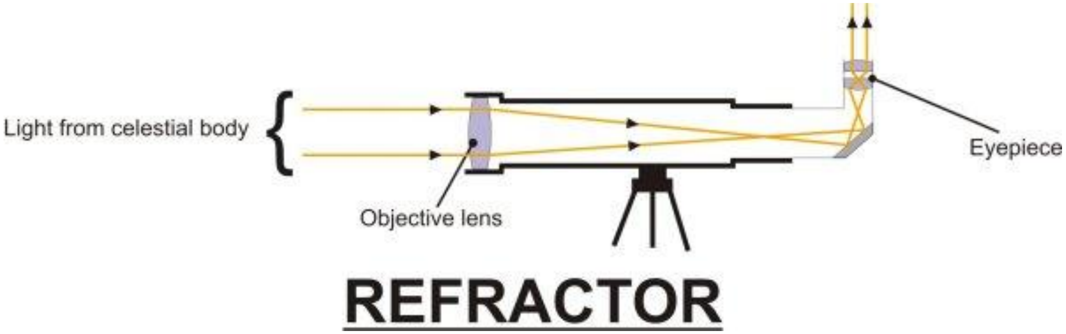
Observational tools for viewing the Cosmos

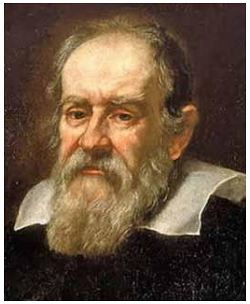
Telescopes: **reflecting** and **refracting**





Isaac Newton
(1642-1727)





Galileo
1564-1642

Angular resolution of a telescope

Angular resolution in radians

Wavelength of light

$$\boxed{\Delta\theta \approx \frac{\lambda}{D}}$$

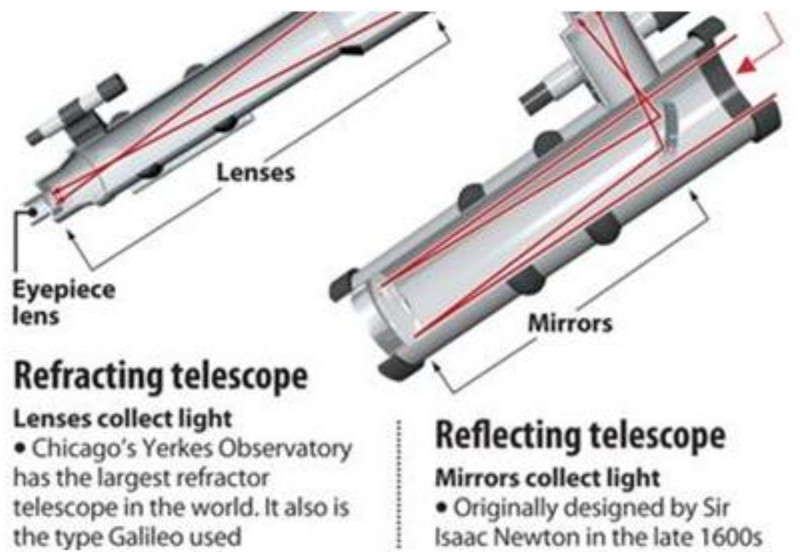
Diameter of telescope aperture

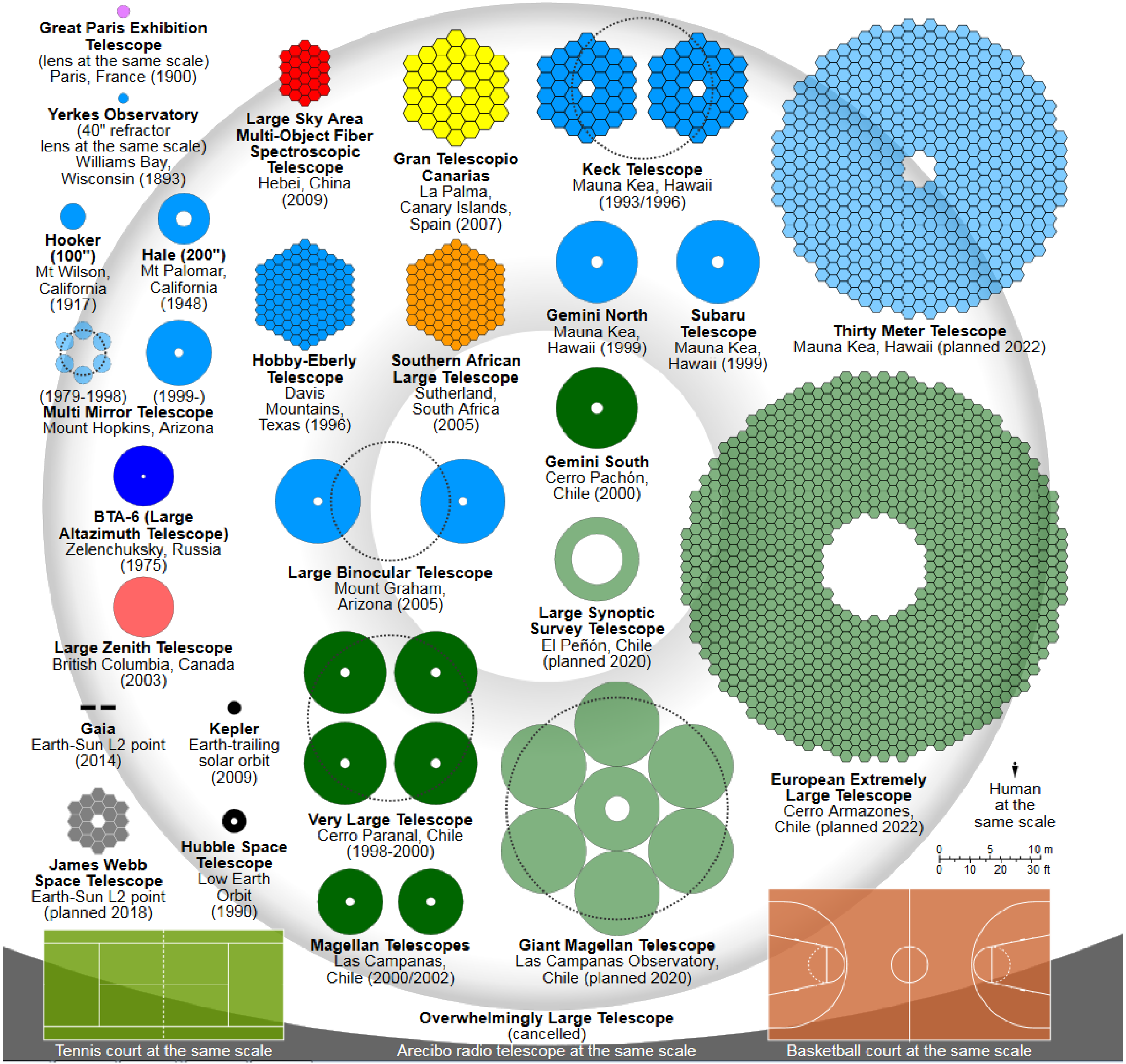
The **Gran Telescopio Canarias** (meaning "Canaries Great Telescope"), also known as GranTeCan or GTC, is a 10.4 m (410 in) reflecting telescope undertaking commissioning observations at the Roque de los Muchachos Observatory on the island of La Palma, in the Canary Islands in Spain, as of July 2009.

$\lambda \approx 10^{-7}\,\mathrm{m}$ visible light

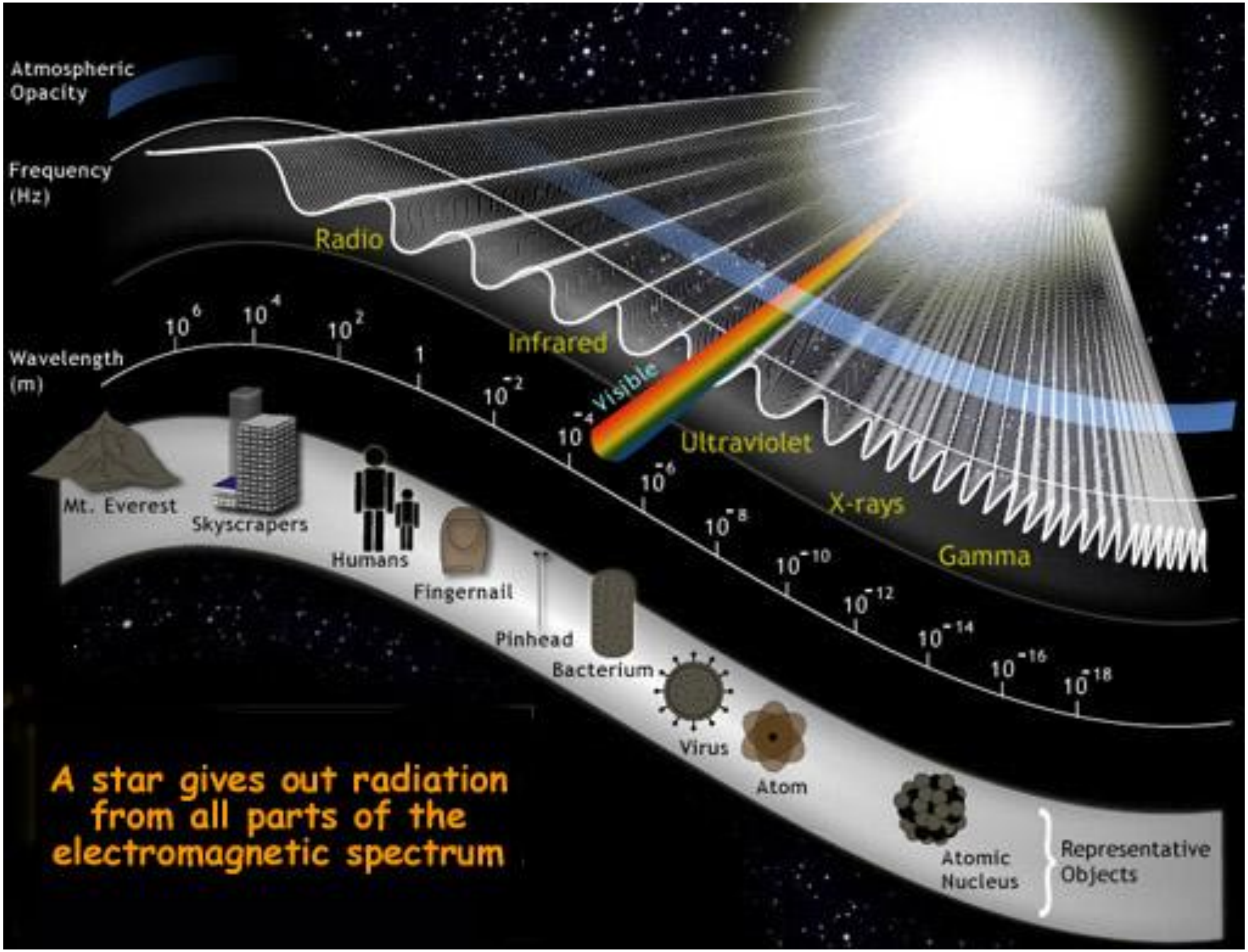
$$\Delta\theta \approx \frac{10^{-7}}{10.4} = 9.6\times10^{-9}\ \text{radians}$$

$$\Delta\theta = 0.00198\ \text{arc seconds}$$



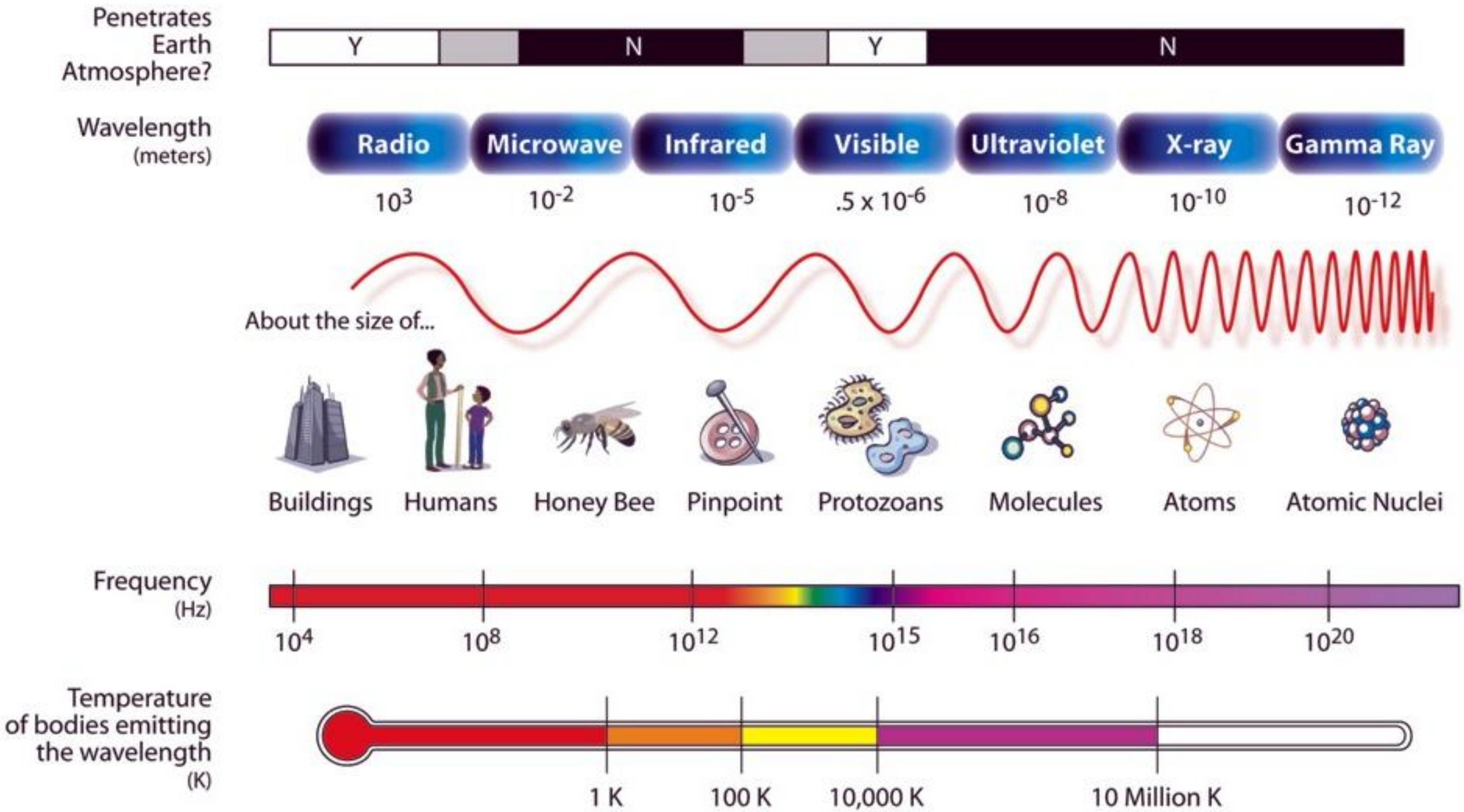


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor lens at the same scale)
Williams Bay, Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
Gemini South
Cerro Pachón, Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale



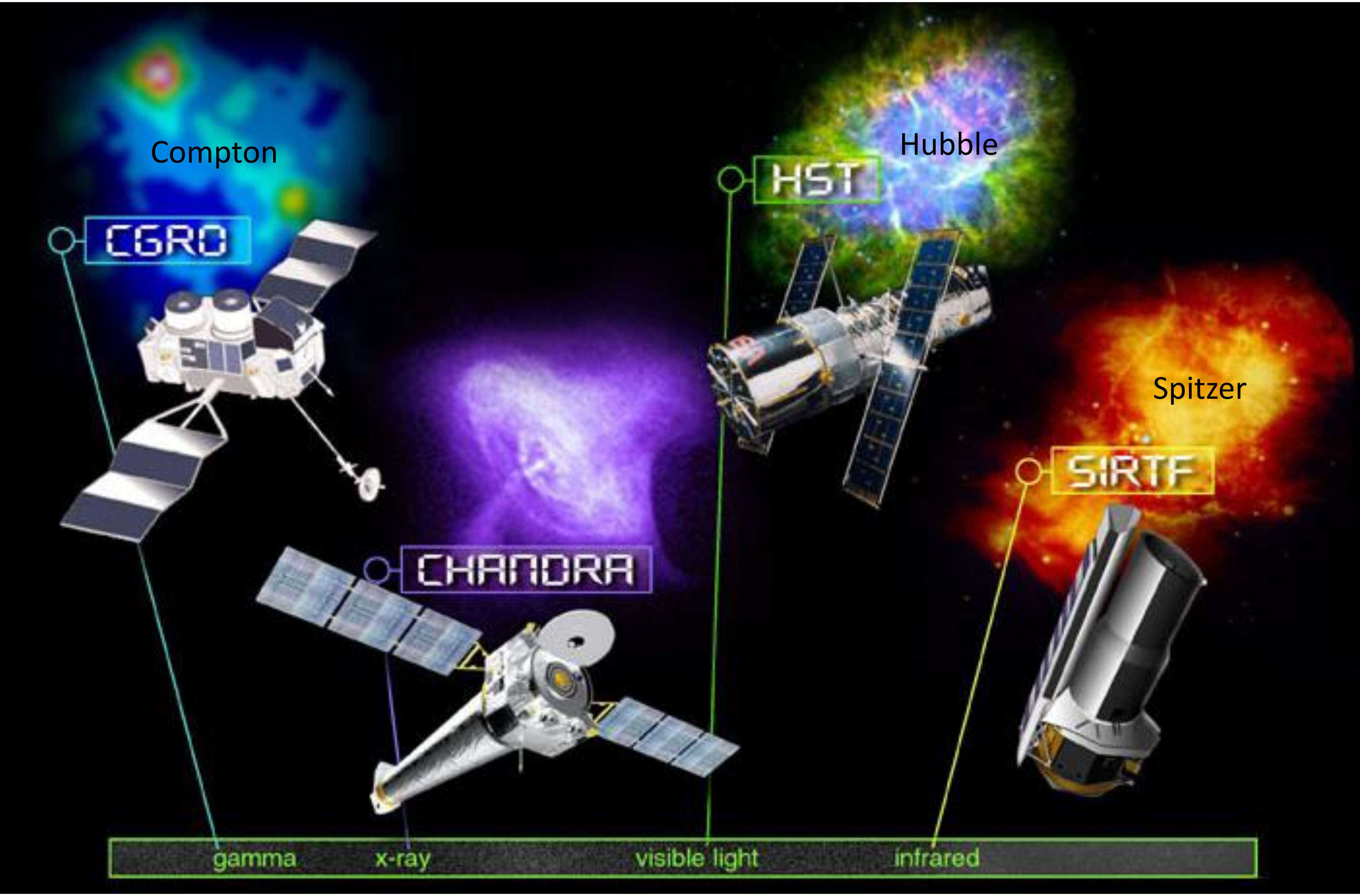
Atmospheric Opacity
Frequency (Hz)
Wavelength (m)
Radio
Infrared
Visible
Ultraviolet
X-rays
Gamma
10^6 10^4 10^2 1 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18}
Mt. Everest
Skyscrapers
Humans
Fingernail
Pinhead
Bacterium
Virus
Atom
Atomic Nucleus
Representative Objects
A star gives out radiation from all parts of the electromagnetic spectrum

THE ELECTROMAGNETIC SPECTRUM



Convert wavelength into frequency using $c = f\lambda$ $\quad c = 2.998 \times 10^8\,\mathrm{ms}^{-1}$

NASA space telescopes

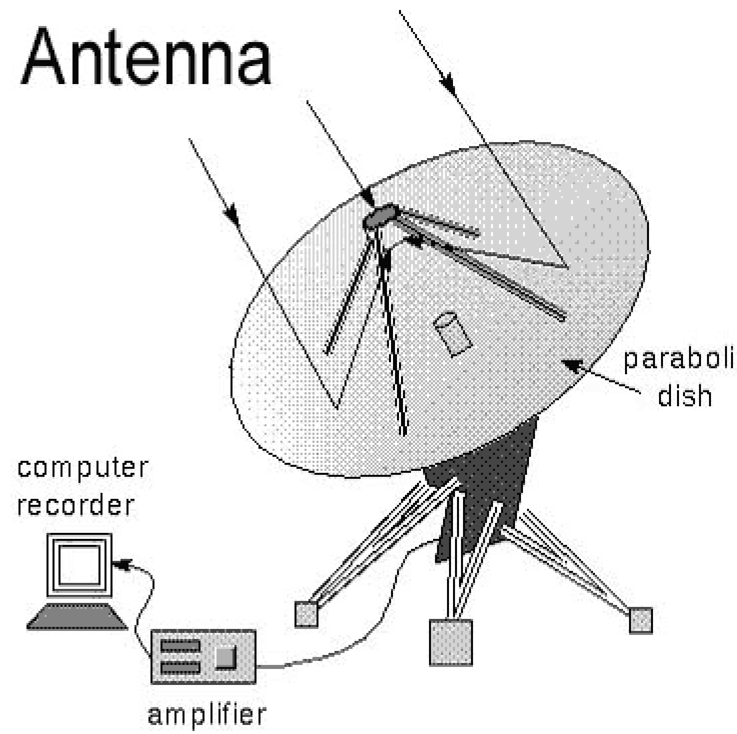


The Hubble space telescope

SETI INSTITUTE

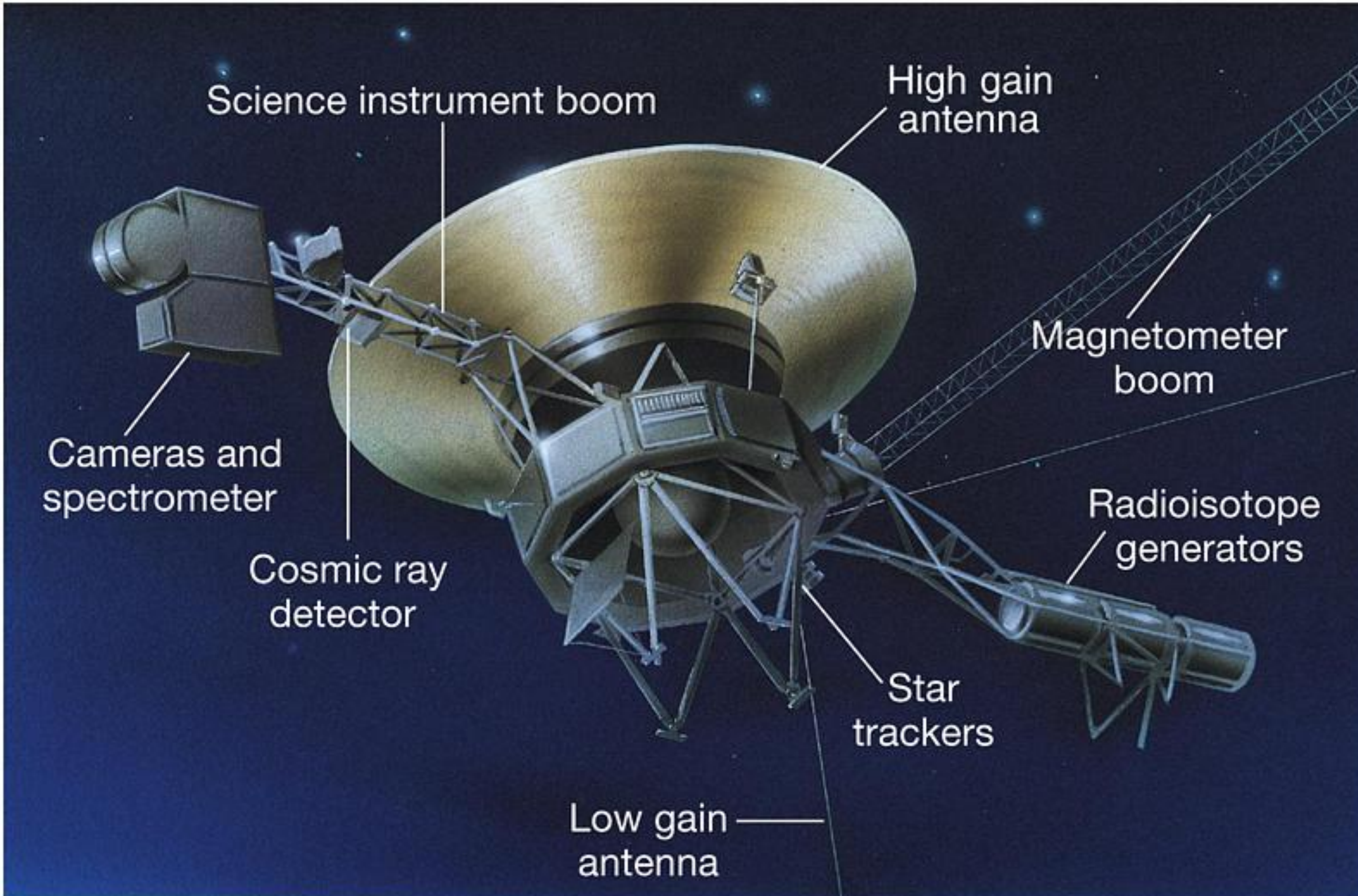
Radio astronomy

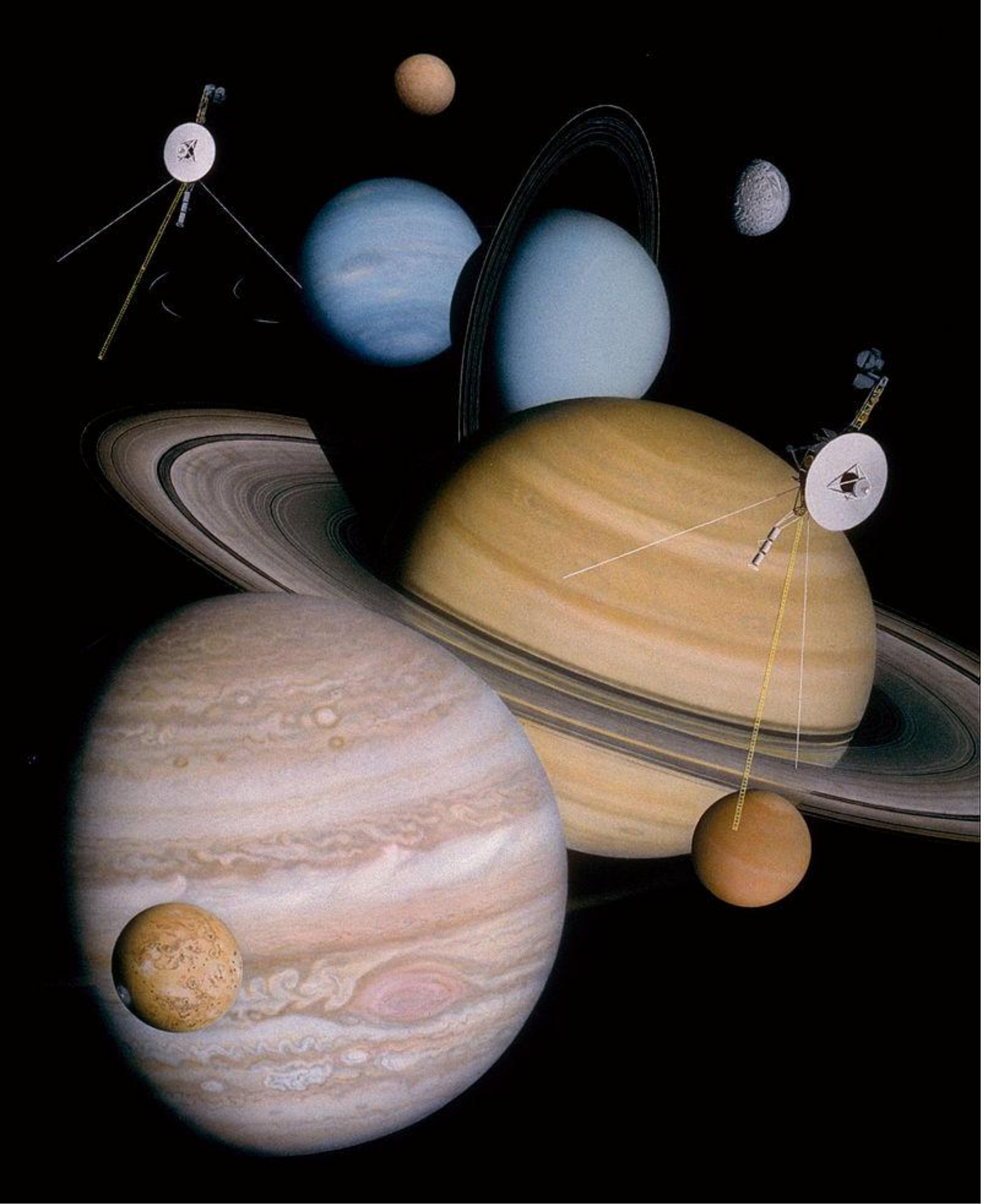
Antenna

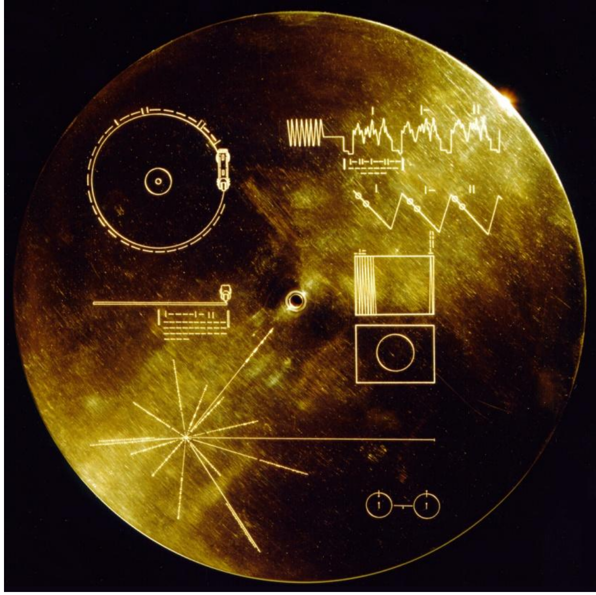


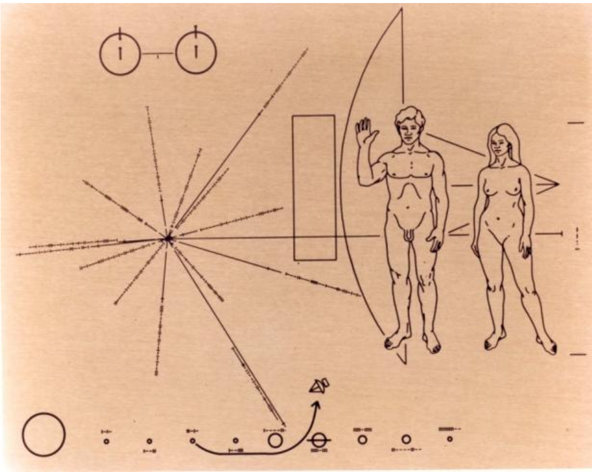
A radio telescope reflects radio waves to a focus at the antenna.

Observations from beyond the Earth .... **Voyager 1 & 2 (1977 -)**

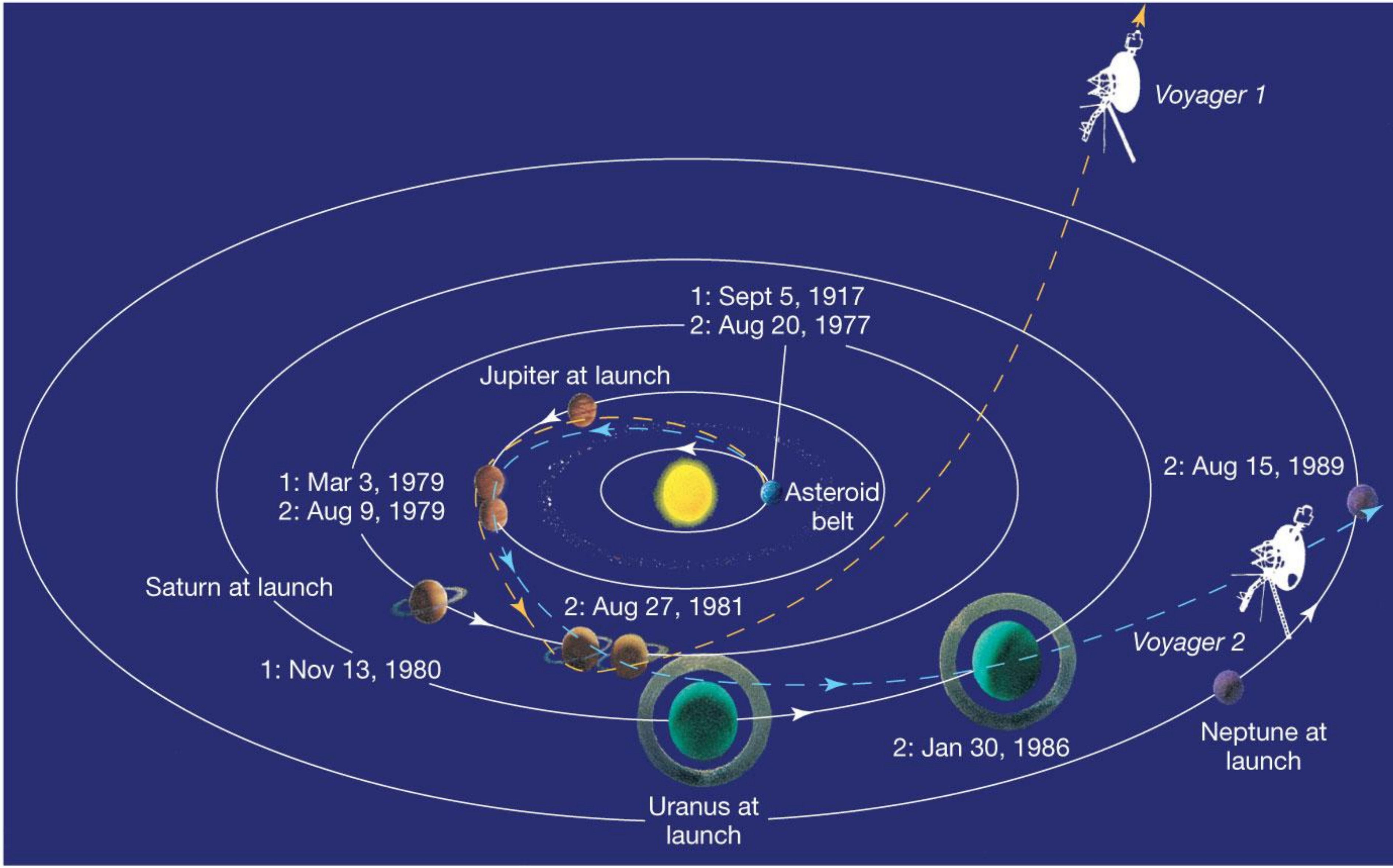








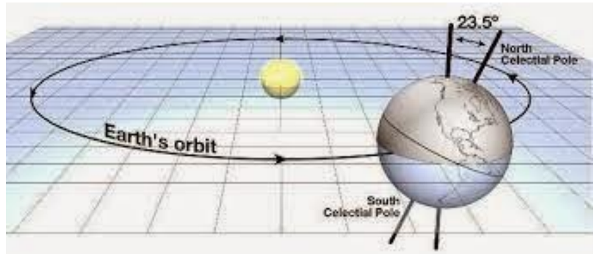
Greetings from Earth!


Voyager 1
1: Sept 5, 1917
2: Aug 20, 1977
Jupiter at launch
1: Mar 3, 1979
2: Aug 9, 1979
Asteroid belt
2: Aug 15, 1989
Saturn at launch
2: Aug 27, 1981
Voyager 2
1: Nov 13, 1980
2: Jan 30, 1986
Neptune at launch
Uranus at launch

Astronomical length scales

Astronomical Unit (approximately the Earth-Sun distance)

$\boxed{1\text{AU} = 1.496 \times 10^{11}\ \text{m}}$



Light-year

$$c = 2.998 \times 10^{8}\ \text{ms}^{-1}$$

$$t_{year} \approx 365 \times 24 \times 3600 = 3.15 \times 10^{7}\ \text{s}$$

$$t_{year} \approx \pi \times 10^{7}\ \text{s}$$

$$1\text{ly} = ct_{year} = \boxed{9.461 \times 10^{15}\ \text{m}}$$

calculated from more precise light speeds and year durations

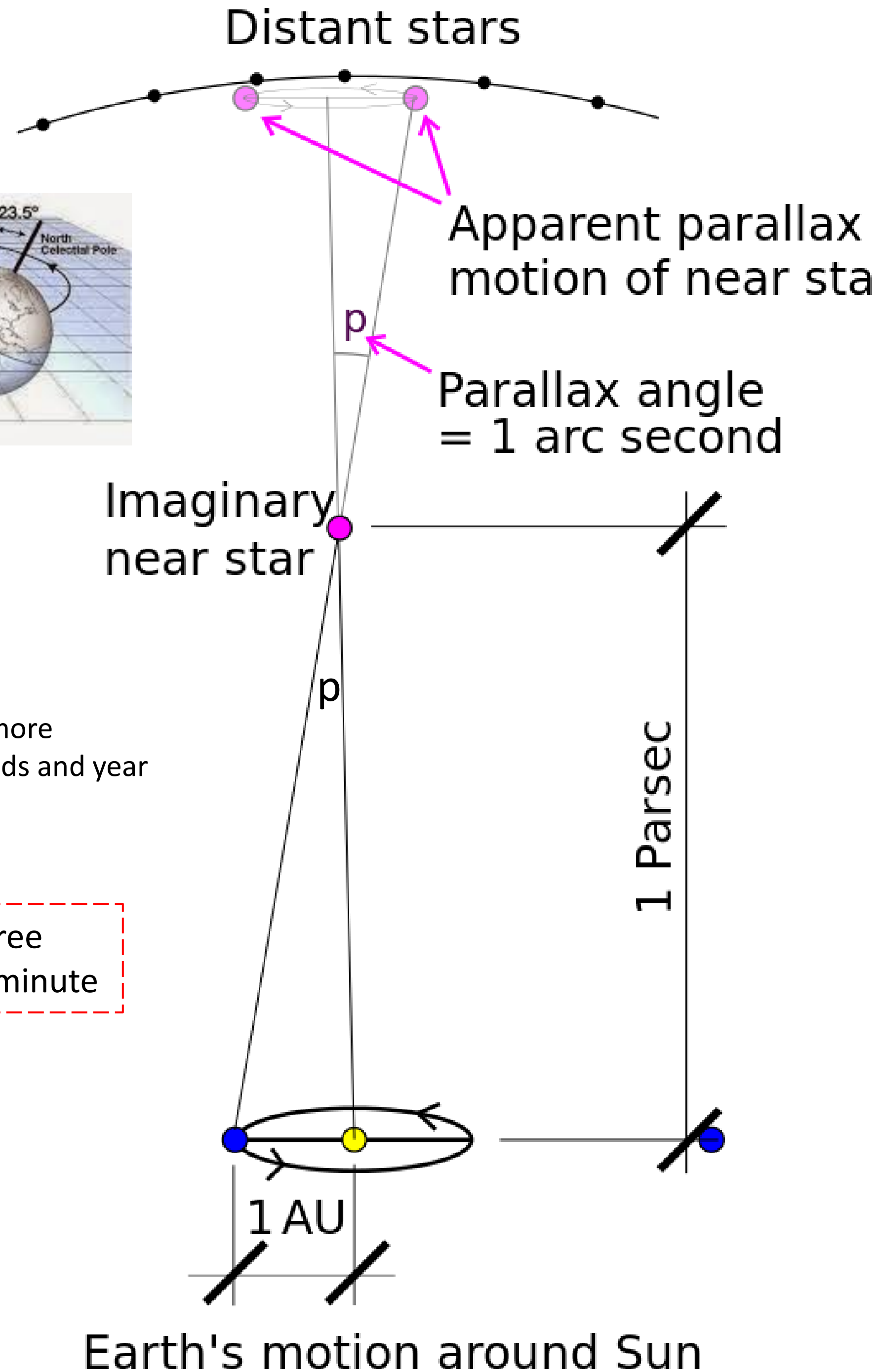
60 arc minutes = 1 degree
60 arc seconds = 1 arc minute

Parsec

$$1\text{AU} = 1\text{pc} \times \tan\left(\frac{1^{\text{o}}}{60 \times 60}\right)$$

$$1\text{pc} = 2.063 \times 10^{5}\ \text{AU}$$

$$\boxed{1\text{pc} = 3.086 \times 10^{16}\ \text{m}}$$

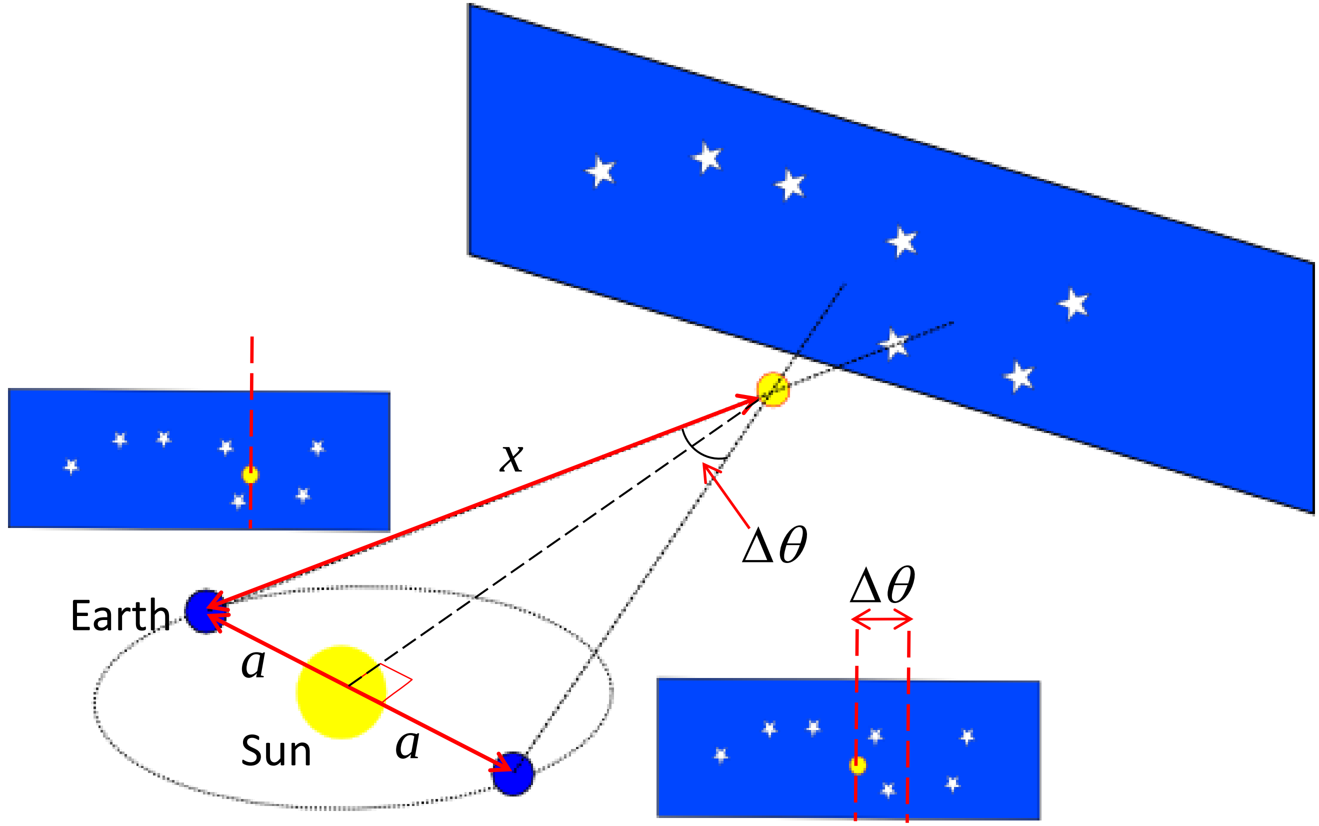


Caution! Parallax is often stated as $\Delta\theta/2$

Measuring distance *x* of stars via **Parallax**

Record the angular change $\Delta\theta$ in the position of a star over the course of a year, i.e. as the Earth orbits the Sun

This assumes the stars are fixed relative to the Earth over this timescale!



a = 1AU = 1.496×10^{11} m

$$x \sin\tfrac{1}{2}\Delta\theta = a$$

$$\boxed{x = \frac{a}{\sin\frac{1}{2}\Delta\theta}}$$

The parallax of our nearest star outside of the solar system (Proxima Centauri) is $\Delta\theta = 1.53626$ arc-seconds

$$\Delta\theta = \frac{1.53626^{\circ}}{3600} \quad \therefore x = \frac{1}{\sin\frac{1}{2}\Delta\theta} = \boxed{268{,}532\,\text{AU}}$$

$$x = \boxed{4.02\times 10^{16}\,\text{m}}$$

$$x = \frac{4.02\times 10^{16}}{9.461\times 10^{15}} = \boxed{4.25\ \text{light-years}}$$

Summary of astronomical distances

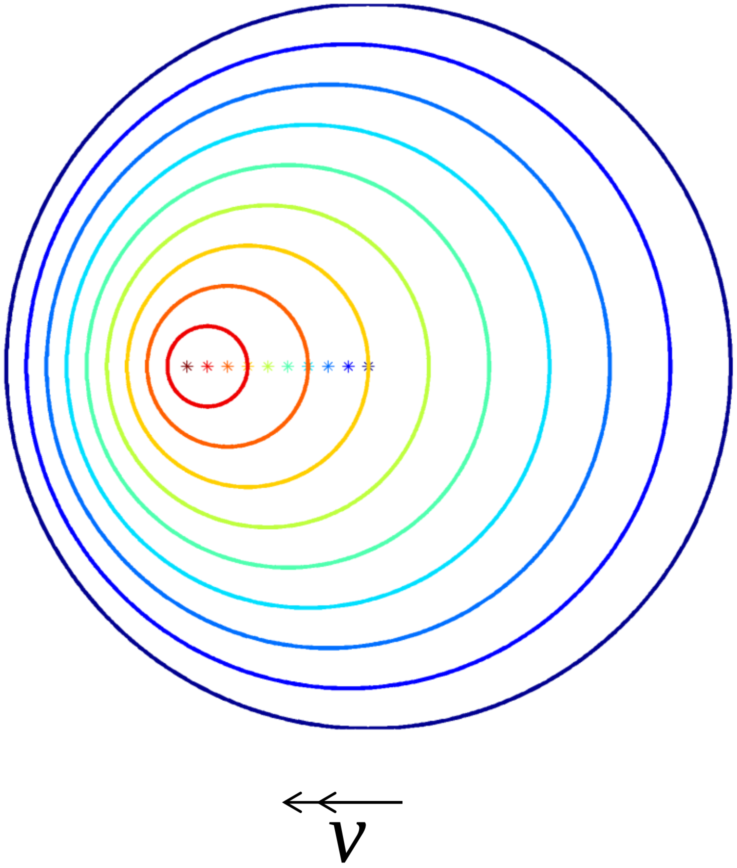
Earth – moon = 1.28 light s
Earth – Sun = 8.3 light min
1pc = 3.26 light yr
Nearest star $\sim$ 4 light yr
Sun – centre of galaxy $\sim$ 25,000 light yr (8 kpc)
To nearest galaxy $\sim$ 2 million light yr (0.75 Mpc)
to distant quasars $\sim$ 10 billion light yr (3 thousand Mpc)

1 AU = 1.496×10^{11} m
1 light year = 9.461×10^{15} m
1 parsec = 3.086×10^{16} m
1Mpc = 10^{6} parsecs = 3.086×10^{22} m

$\boxed{c = f\lambda}$

Doppler shift method for measuring radial velocity

If an object emitting radiation at frequency *f* moves radially towards an observer at velocity *v*, the observer will measure a *slightly higher frequency* of radiation as the emitted waves 'bunch up'.



Velocity of emitter towards observer

Frequency of emitted radiation

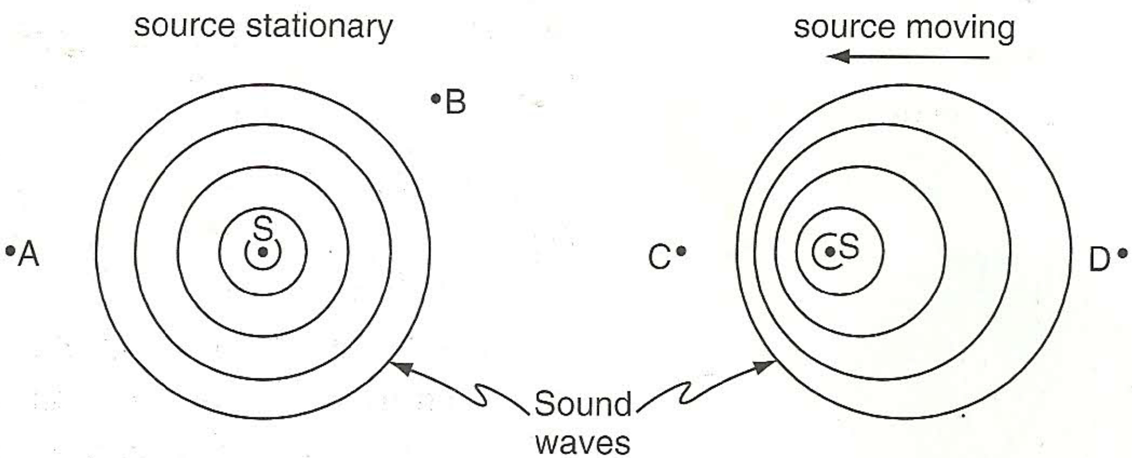
frequency change

$$\boxed{\Delta f = \frac{v}{c} f}$$

Speed of radiation

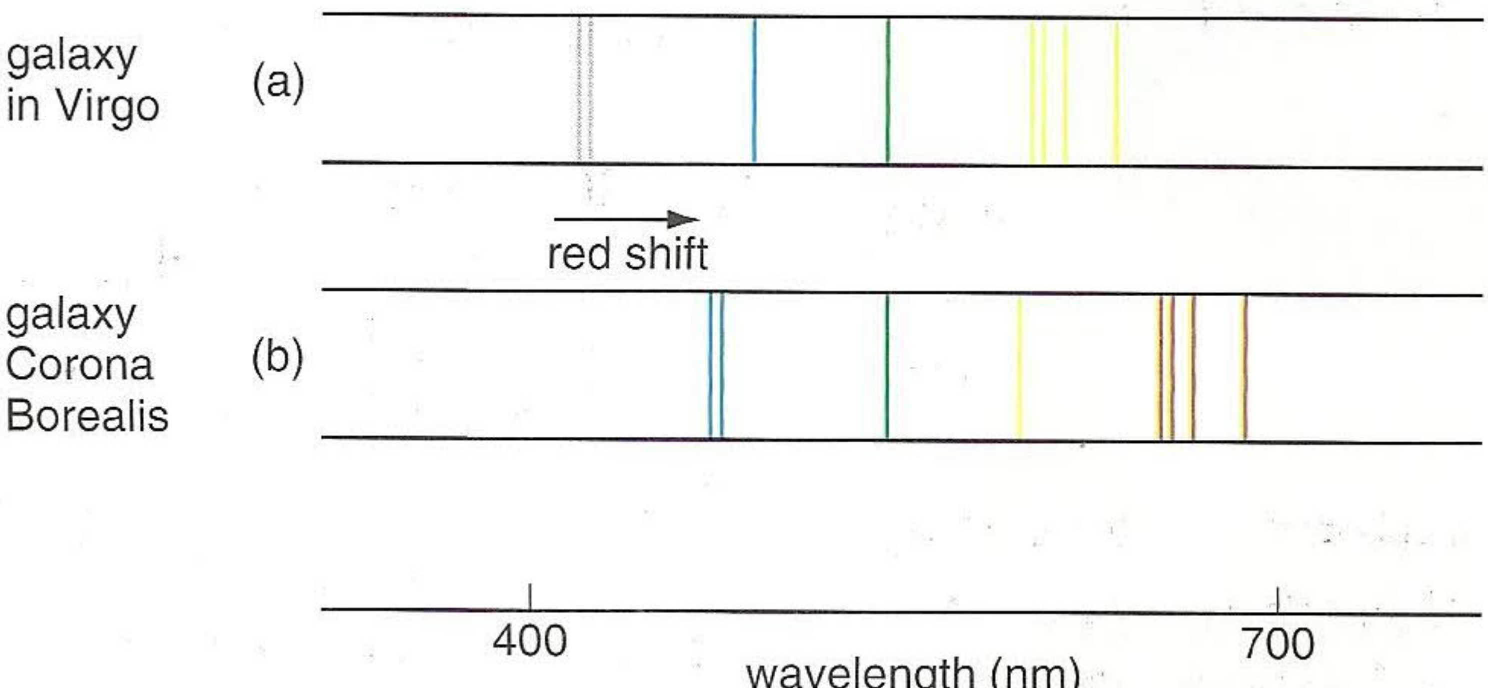
Note this formula is 'Classical'. It is valid when v << c, otherwise a relativistic version must be used

Christian Doppler
1803-1953

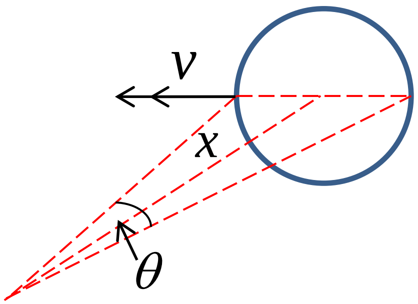


Redshift z is the fractional change in wavelength of light due to the doppler effect

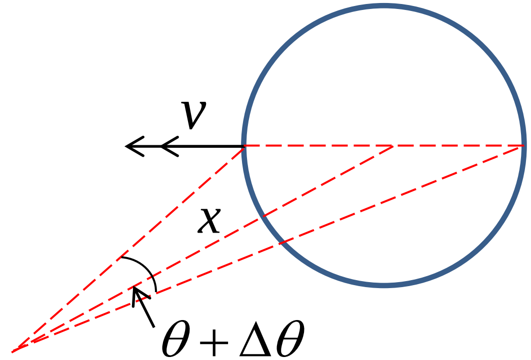
$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emmitted}}}{\lambda_{\text{emmitted}}}$$



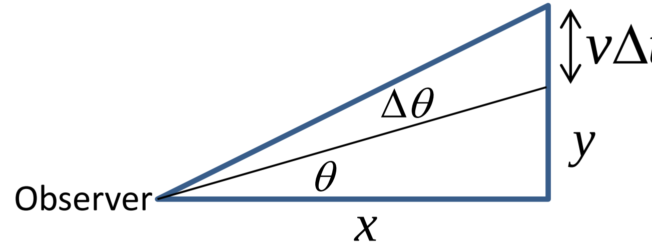
Using **radial velocity** calculation (via Doppler shift) to calculate distances of stars



Radially expanding gas cloud at time *t*



Radially expanding gas cloud at time *t* + Δ*t*



$$y = x \tan\theta$$

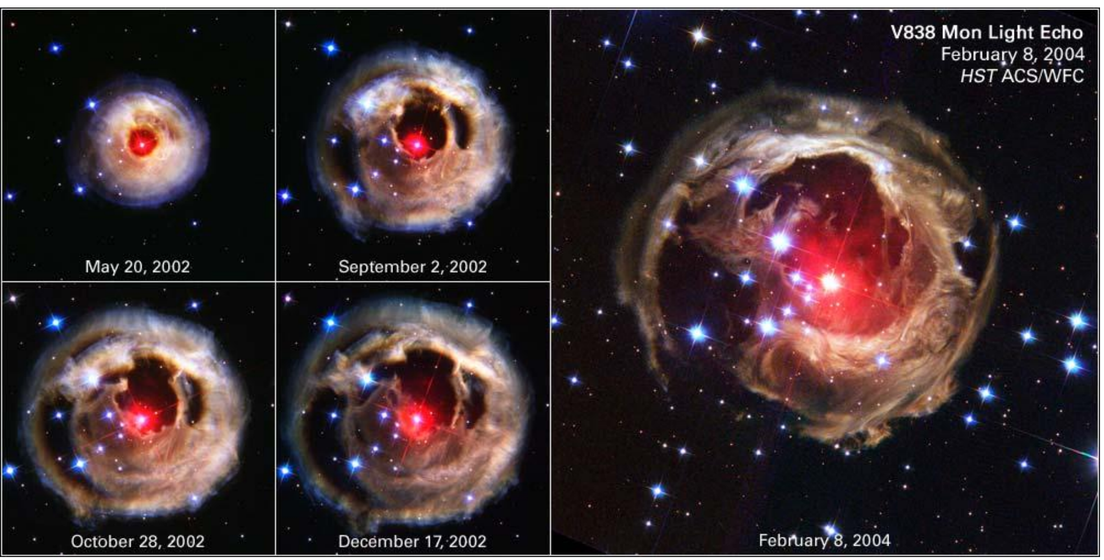
$$\tan(\theta + \Delta\theta) = \frac{v\Delta t + y}{x}$$

$$x = \frac{v\Delta t + x\tan\theta}{\tan(\theta + \Delta\theta)}$$

$$x\left(\tan(\theta + \Delta\theta) - \tan\theta\right) = v\Delta t$$

$$x = \frac{v\Delta t}{\tan(\theta + \Delta\theta) - \tan\theta}$$

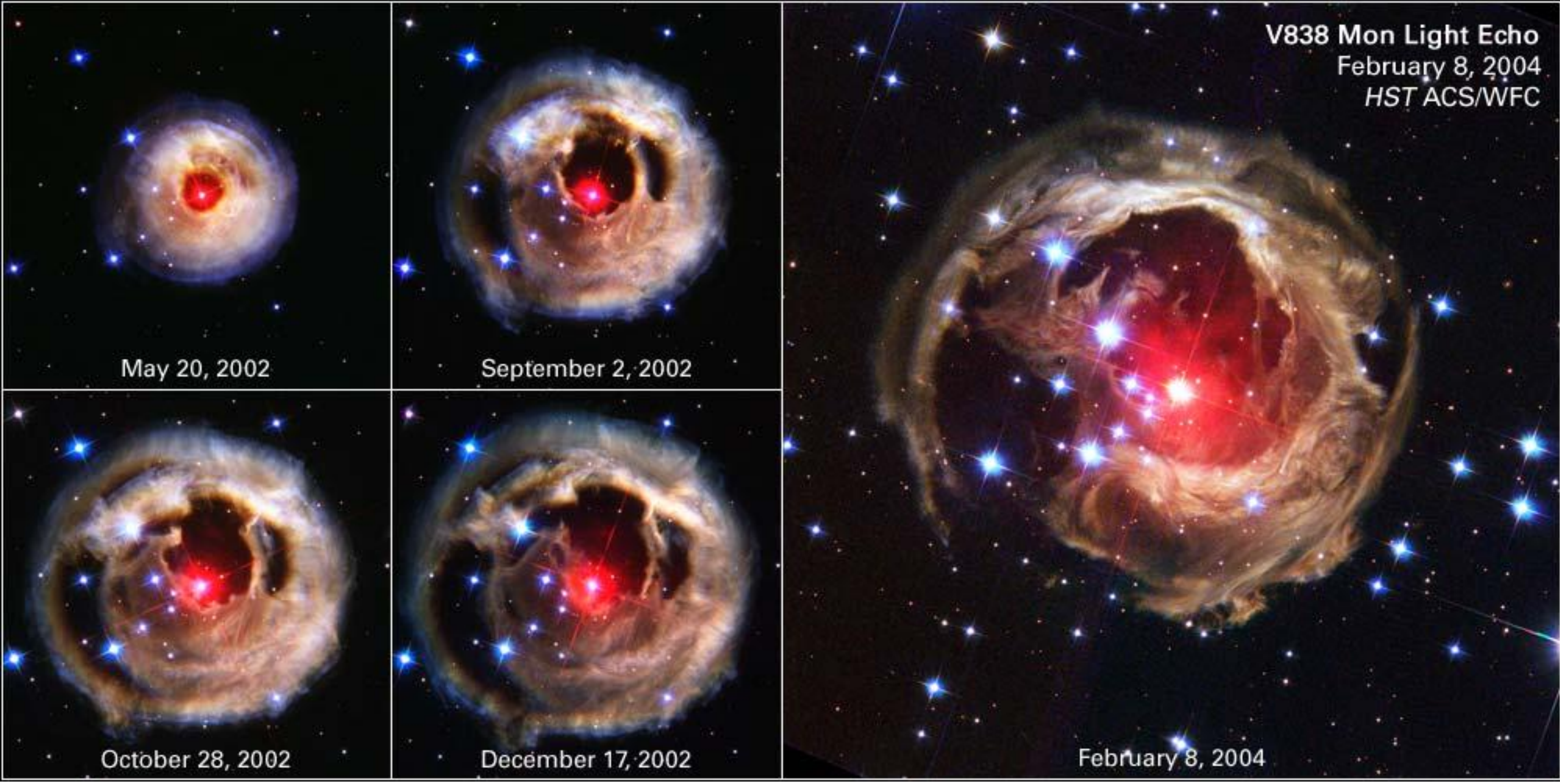
$$\boxed{x \approx \frac{v\Delta t}{\Delta\theta}}$$



*Measure *v* from Doppler shift of spectrum

*Measure angular change $\Delta\theta$ between observations

*Hence obtain distance of star at centre of expanding gas cloud



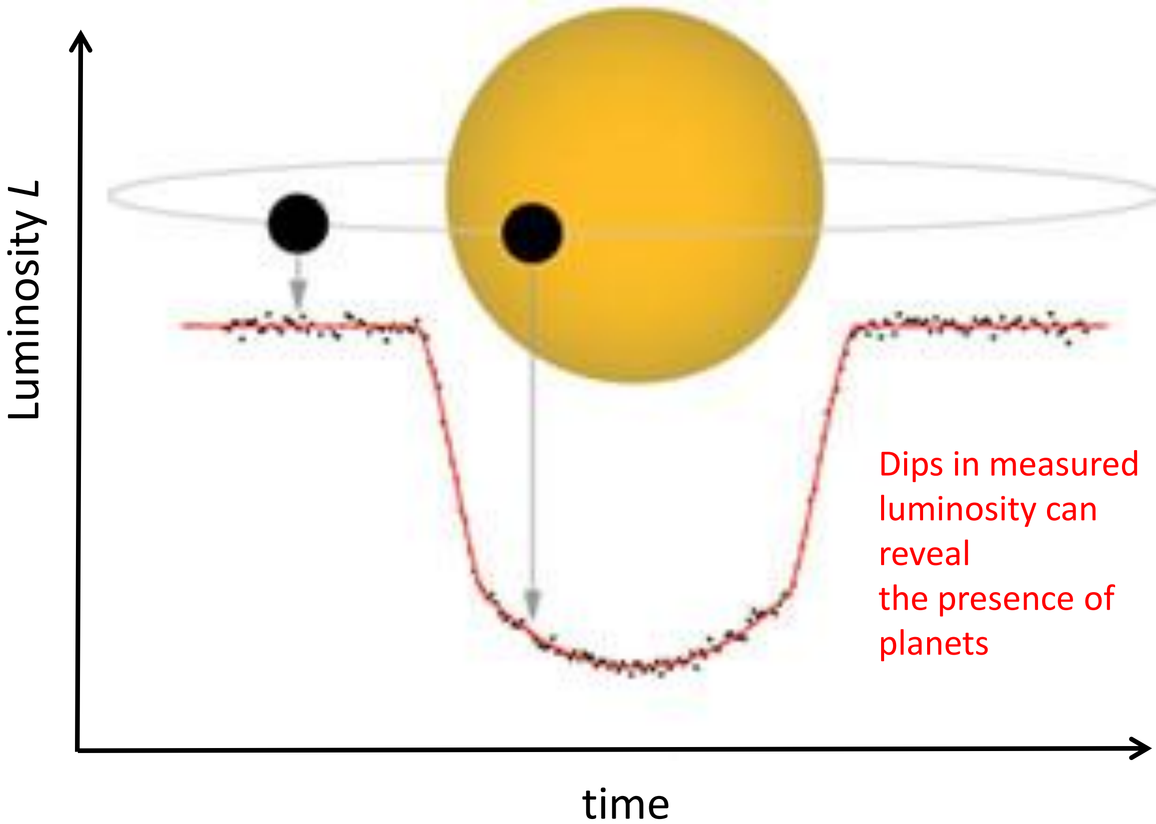
*Measure v from Doppler shift of spectrum
*Measure angular change $\Delta\theta$ between observations
*Hence obtain distance of star at centre of expanding gas cloud

$$\boxed{\Delta f = \frac{v}{c} f}$$

$$\boxed{x \approx \frac{v\Delta t}{\Delta\theta}}$$

The key challenge here is to work out what the **emission frequency f** should be, in order to work out the doppler shift

Luminosity method for measuring distances, and detecting planets!



Luminosity L is the light power generated by a star

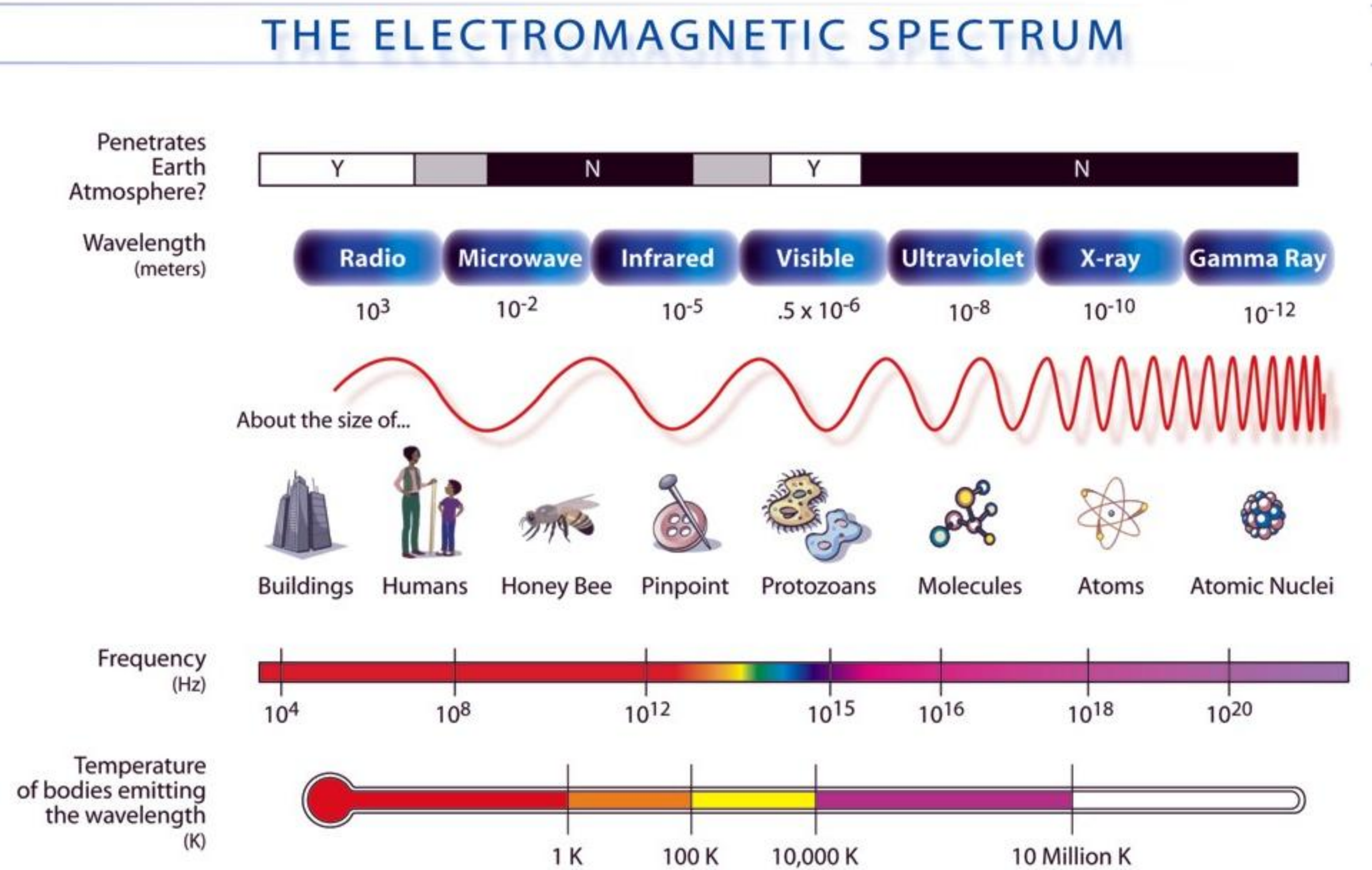
$$\boxed{B = \frac{L}{4\pi x^2}}$$

If the star is a distance x away then the 'brightness' B (defined as the power per unit area) is L divided by the area of a sphere of radius x

If we know the luminosity of a certain type of star (indicated by its *spectrum*) then we can use the measured brightness to work out how far away it is.

$$\boxed{L_{\odot} = 3.846 \times 10^{26}\,\mathrm{W}}$$

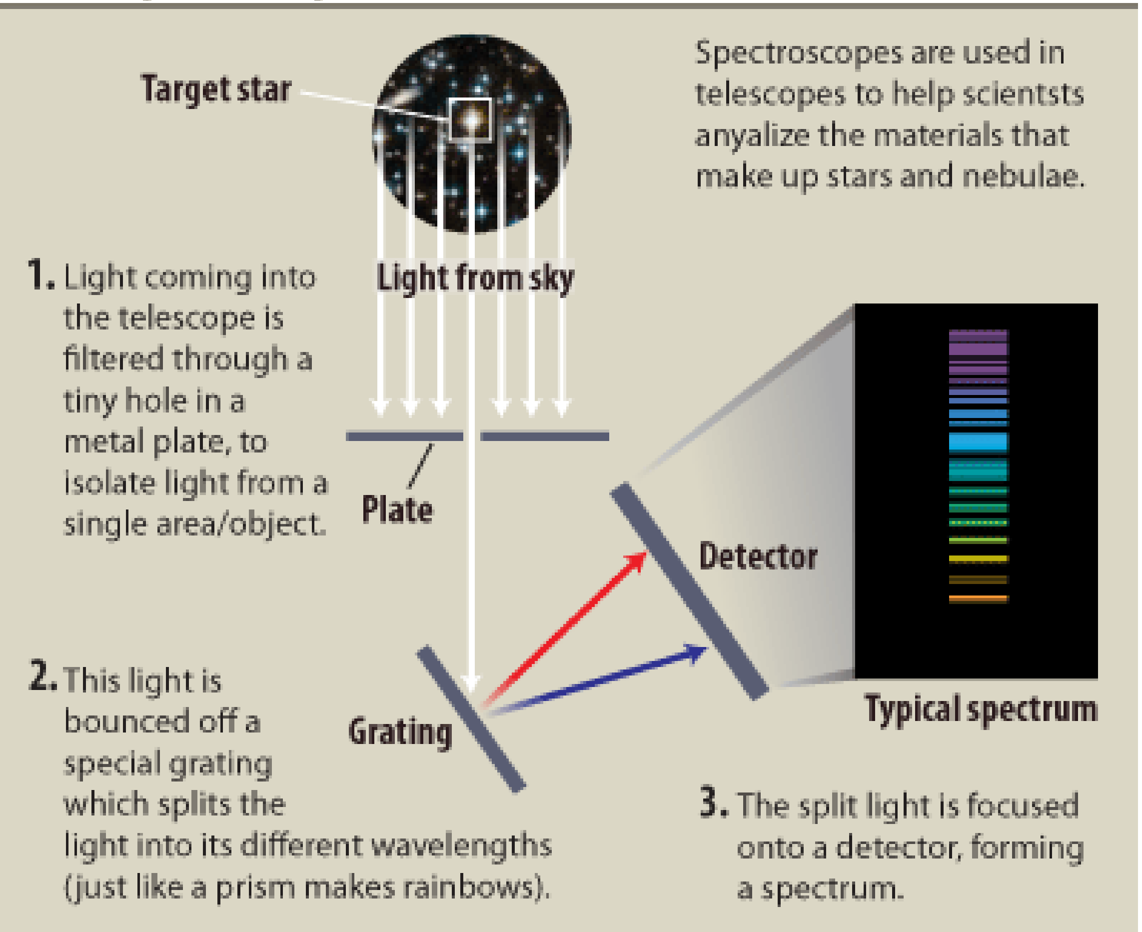
Current luminosity of our Sun

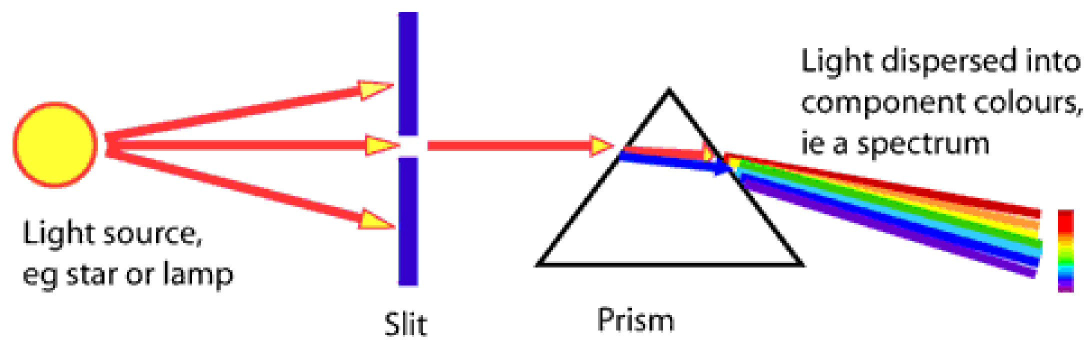


Convert wavelength into frequency using $c = f\lambda$

$$c = 2.998 \times 10^{8}\,\mathrm{ms}^{-1}$$

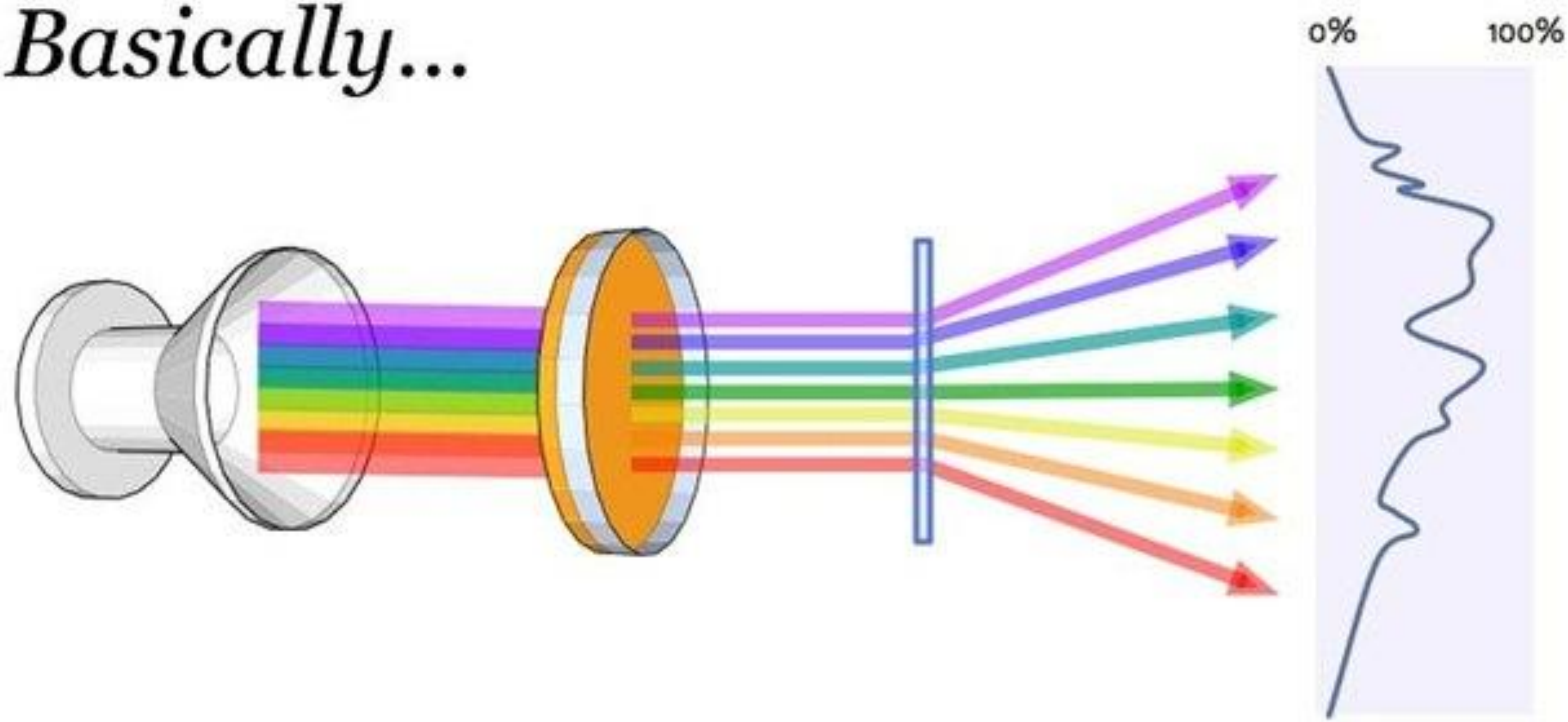
How a Spectroscope Works





Dispersion of light through a prism

Basically…

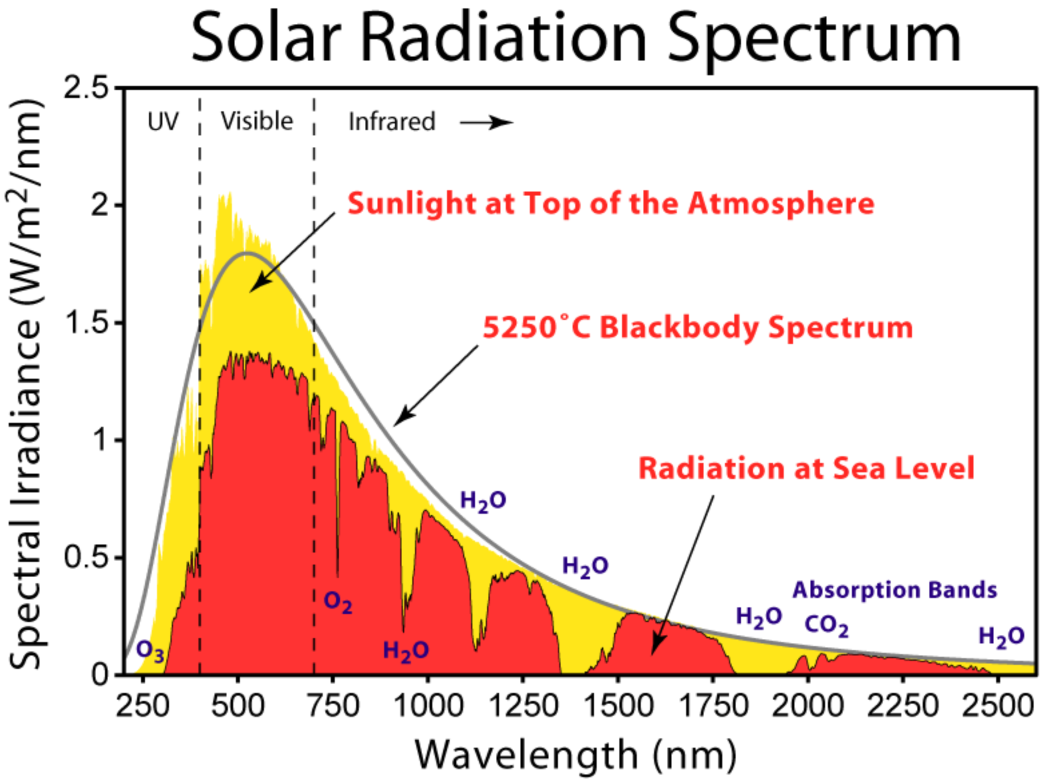


1. A broad-spectrum light (halogen, incandescent) is shone through a sample

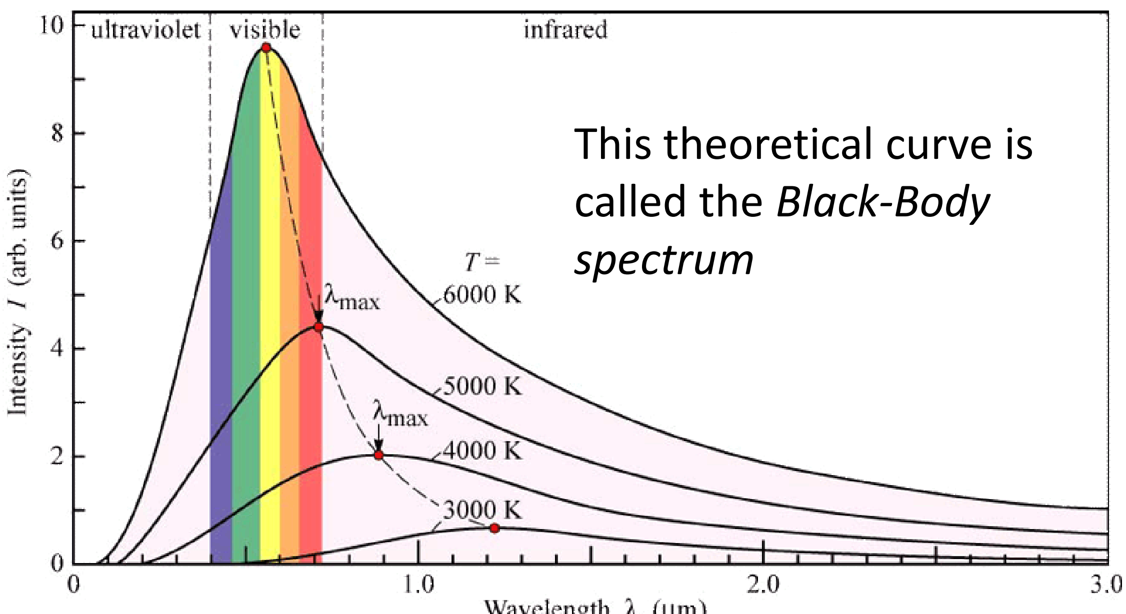
2. Some colors are absorbed more than others depending on its composition

3. Diffraction grating splits light into colors so they can be measured separately

4. A webcam measures each color and graphs their intensities. This is compared to known samples.



Note solar energy is absorbed in atmosphere by oxygen, water vapour, carbon dioxide etc. Hence *dips* in the solar spectra at sea level.



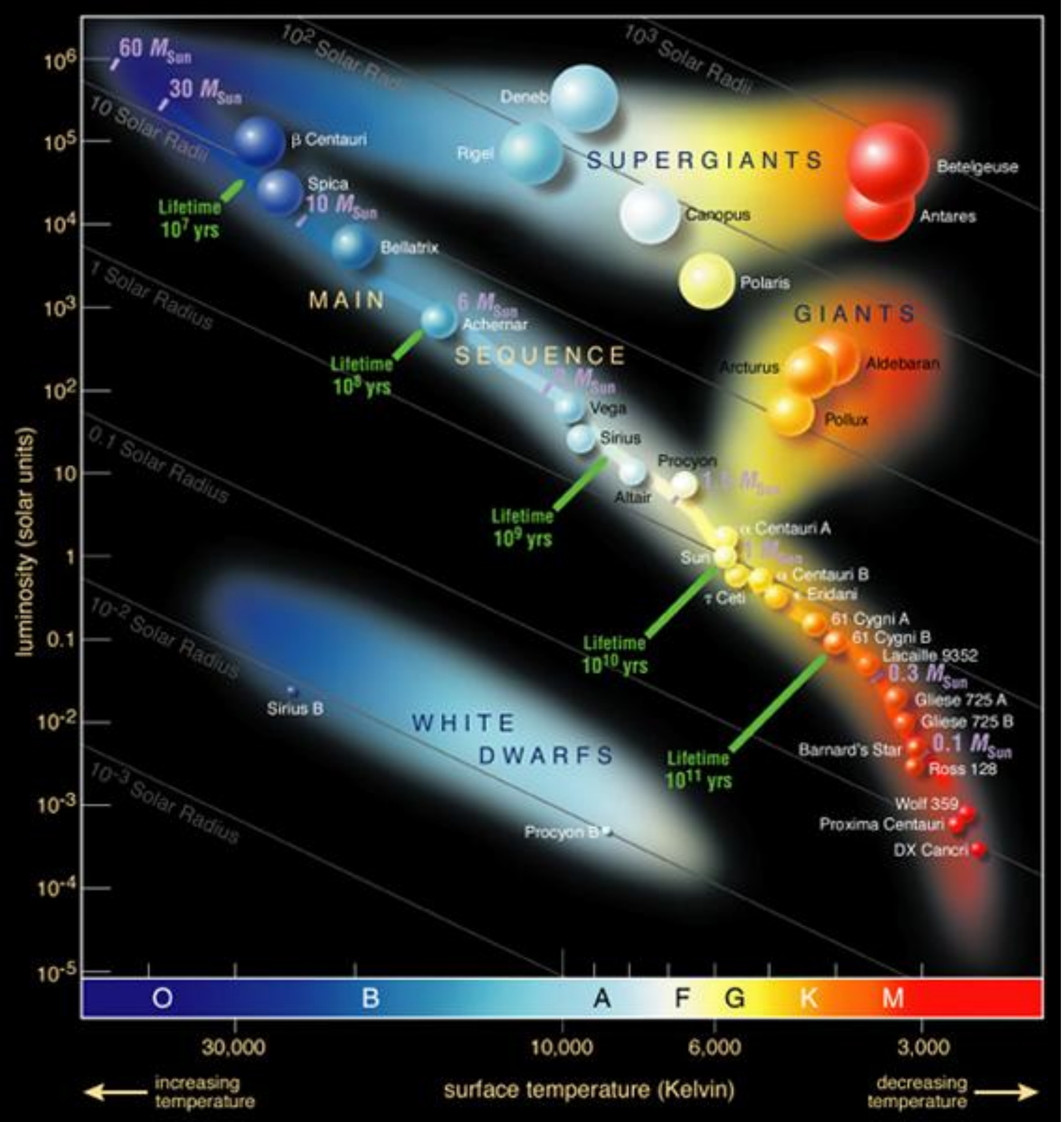
This theoretical curve is called the *Black-Body spectrum*

Measure **surface temperature** of a star from the spectral shape

(i.e. brightness at different wavelengths)

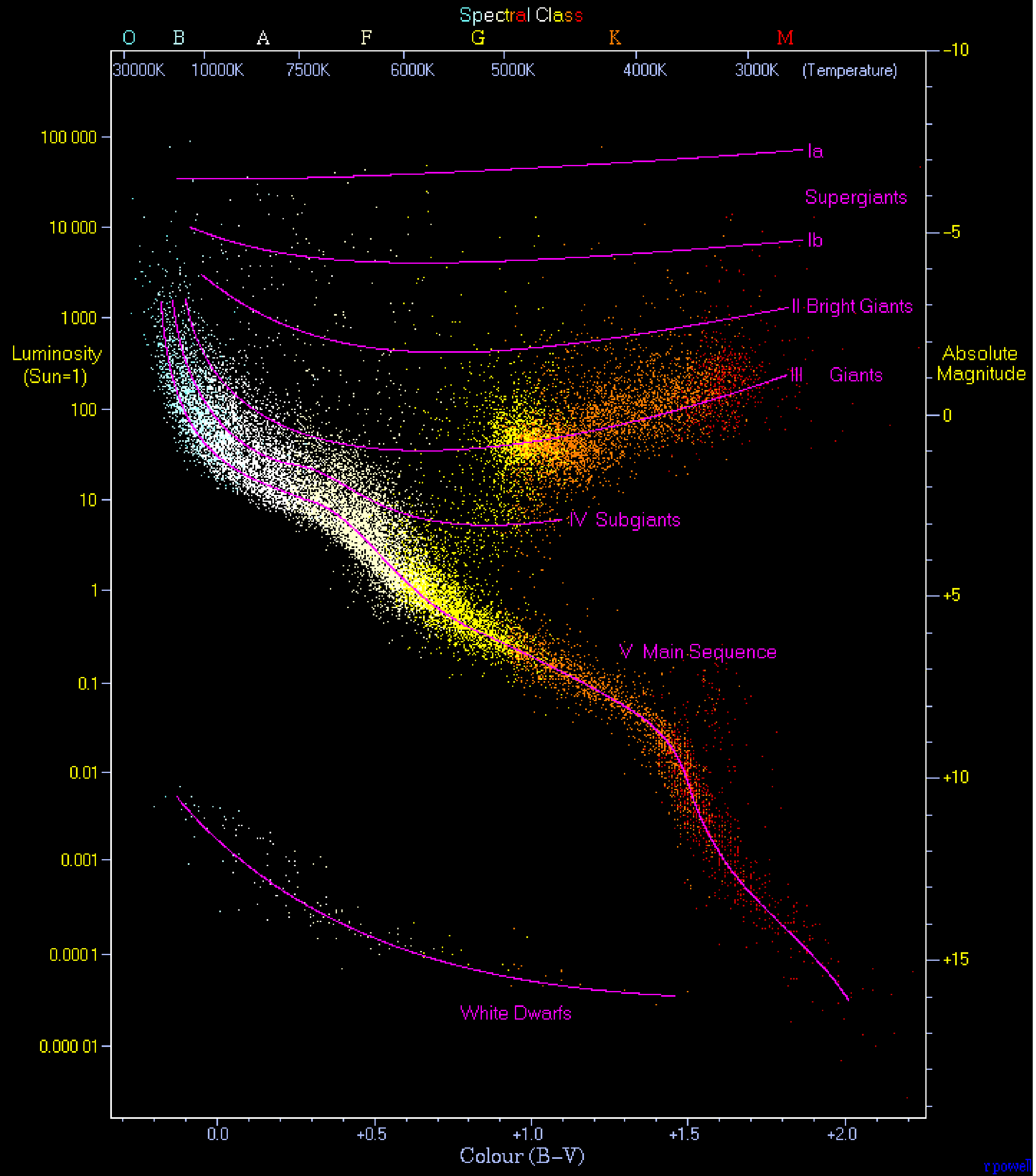
Convert wavelength into frequency using

$$c = f\lambda$$



Hertzsprung-Russell diagram

1910 by Ejnar Hertzsprung and Henry Norris Russell

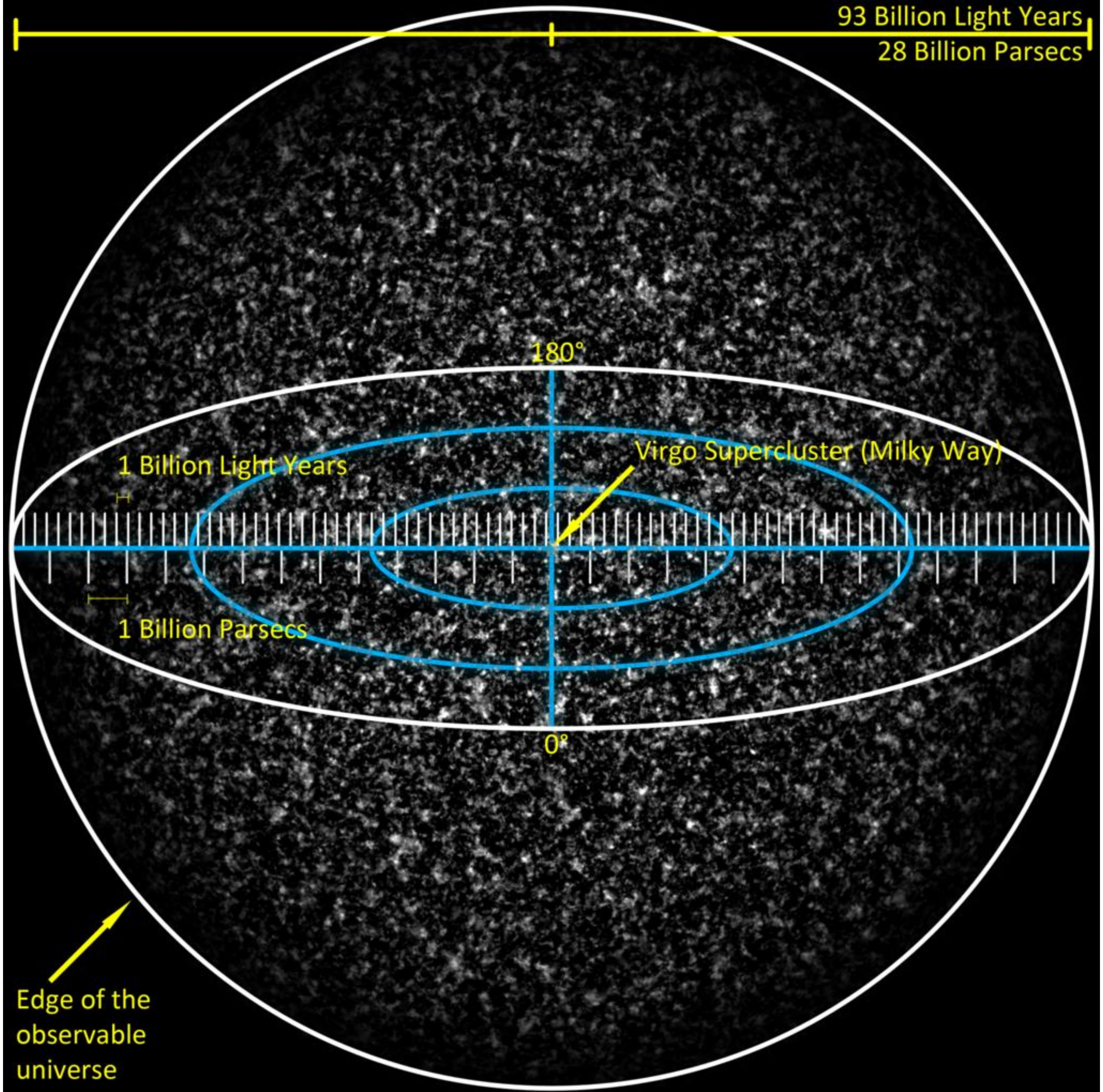


Hertzsprung–Russell diagram with 22,000 stars plotted from the Hipparcos Catalogue and 1,000 from the Gliese Catalogue of nearby stars.

Stars tend to fall only into certain regions of the diagram. The most prominent is the diagonal, going from the upper-left (hot and bright) to the lower-right (cooler and less bright), called the **main sequence**.

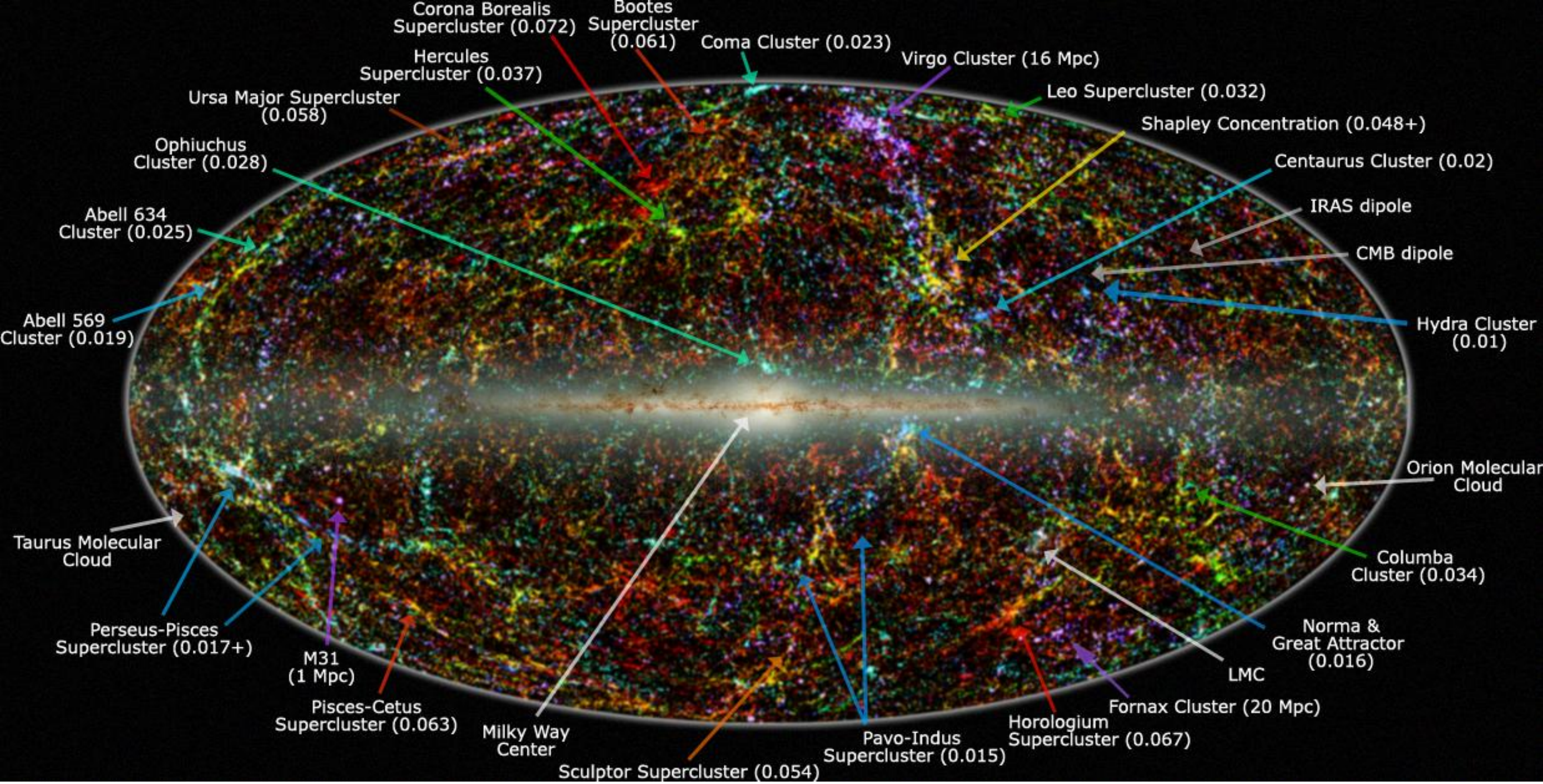
In the lower-left is where **white dwarfs** are found, and above the main sequence are the **subgiants**, **giants** and **supergiants**.

The Sun is found on the main sequence at luminosity 1 (absolute magnitude 4.8) and B−V colour index 0.66 (temperature 5780 K, spectral type G2V).


93 Billion Light Years
28 Billion Parsecs
180°
Virgo Supercluster (Milky Way)
1 Billion Light Years
1 Billion Parsecs
0°
Edge of the observable universe

NASA; ESA; G. Illingworth, D. Magee, and P. Oesch, University of California, Santa Cruz; R. Bouwens, Leiden University; and the HUDF09 Team

The Hubble eXtreme Deep Field (XDF) was completed in September 2012 and shows the farthest galaxies ever photographed. Except for the few stars in the foreground (which are bright and easily recognizable because only they have diffraction spikes), every speck of light in the photo is an individual galaxy, some of them as old as 13.2 billion years; the observable universe is estimated to contain more than 200 billion galaxies.



Panoramic view of the entire near-infrared sky reveals the distribution of galaxies beyond the Milky Way. The image is derived from the **2MASS Extended Source Catalogue** (XSC)—more than 1.5 million galaxies, and the Point Source Catalogue (PSC)--nearly 0.5 billion Milky Way stars. The galaxies are colour coded by redshift (numbers in parentheses). Blue/purple are the nearest sources ($z < 0.01$); green are at moderate distances ($0.01 < z < 0.04$) and red are the most distant sources that 2MASS resolves ($0.04 < z < 0.1$). The map is projected with an equal area Aitoff in the Galactic system (Milky Way at centre).

IPAC/Caltech, by Thomas Jarrett - "Large Scale Structure in the Local Universe: The 2MASS Galaxy Catalog", Jarrett, T.H. 2004, PASA, 21, 396