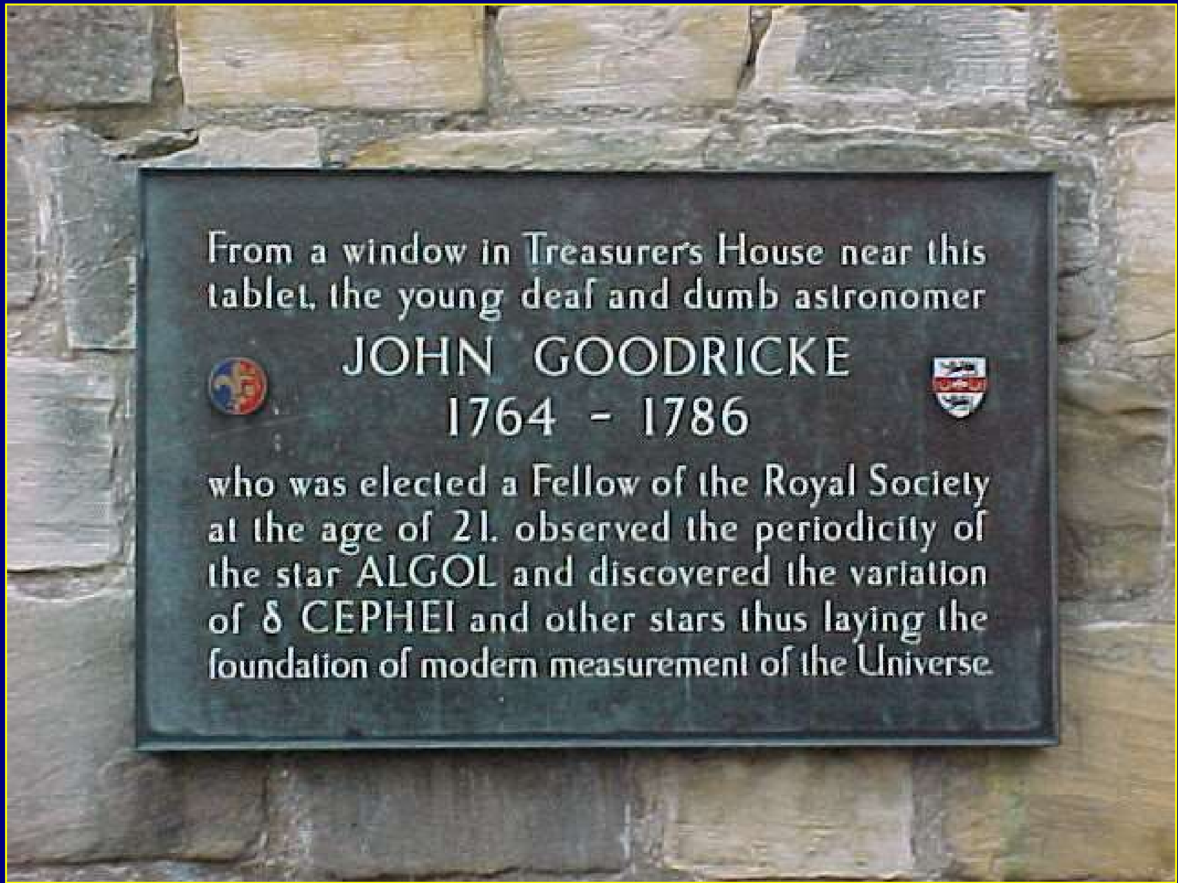
THE COSMOLOGICAL DISTANCE SCALE

How do astronomers measure the distances to stars and galaxies?

Near York Minster in England is this interesting plaque which refers to one of the methods discovered in the 18th century. We shall return to it in due course, but first some basics.



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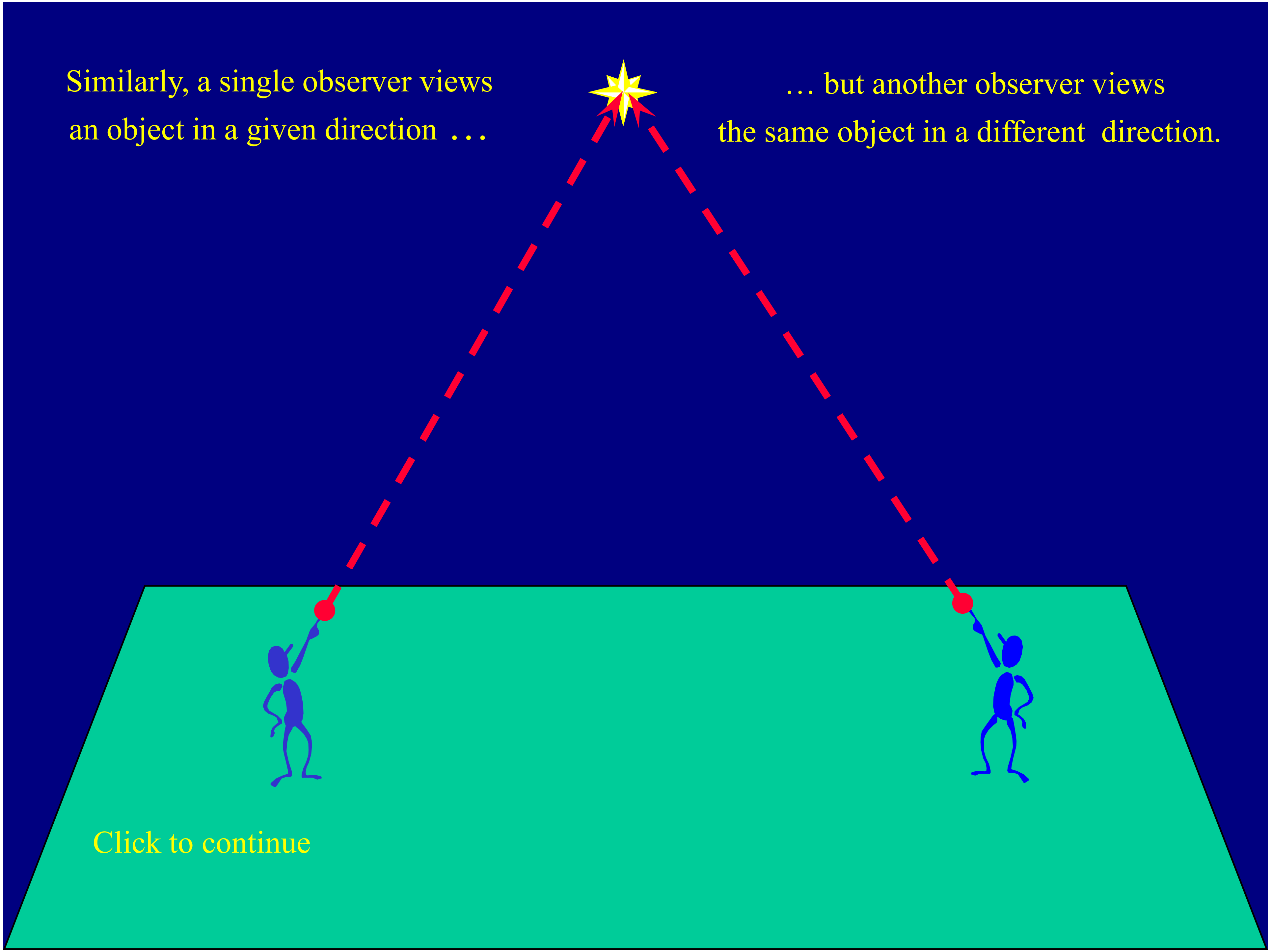
David Le Conte, FRAS

If we look at a nearby object such as a finger with one eye and then the other eye it appears to jump back and forth against the distant background.


Similarly, a single observer views
an object in a given direction . . .
… but another observer views
the same object in a different direction.
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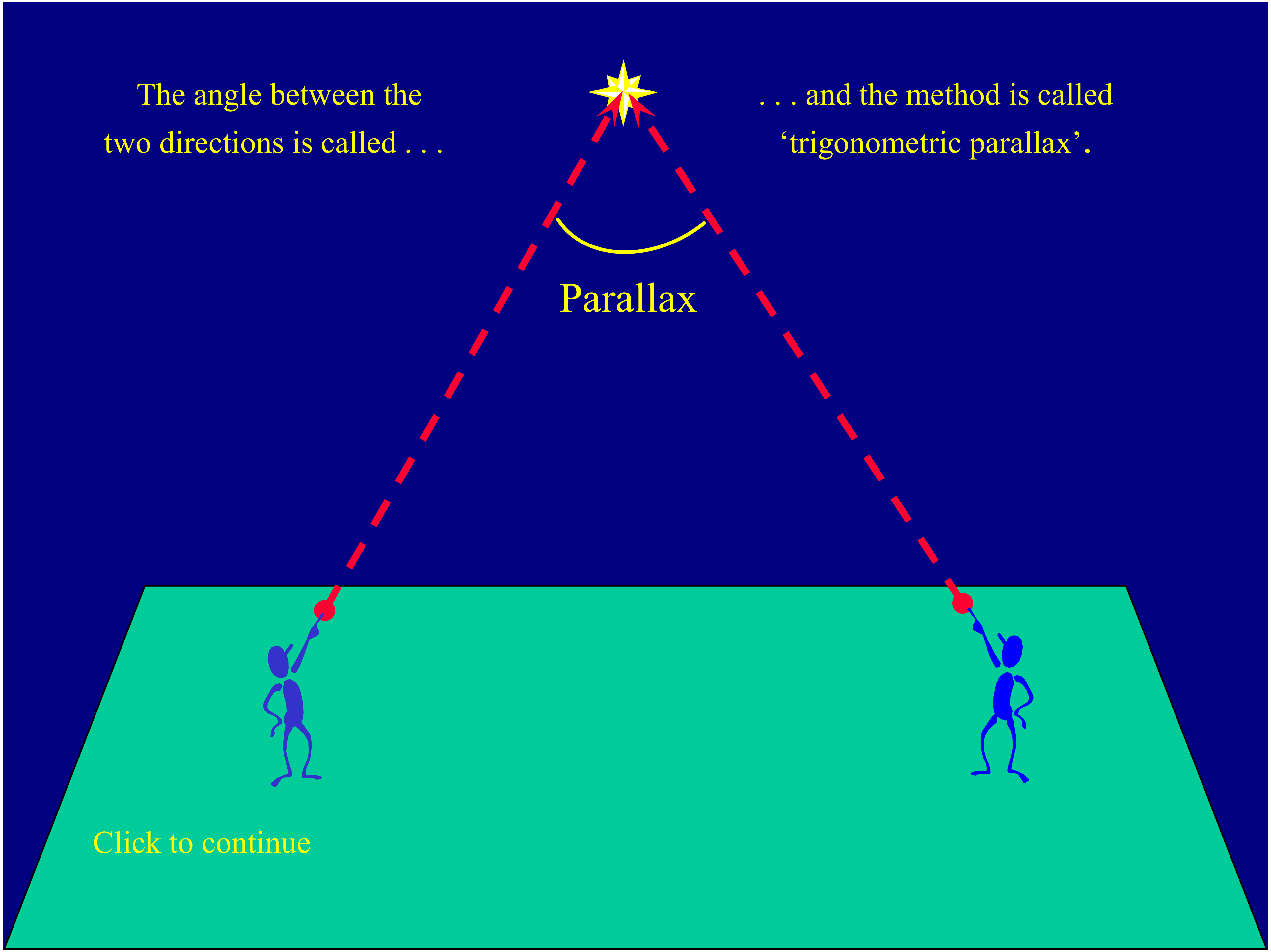
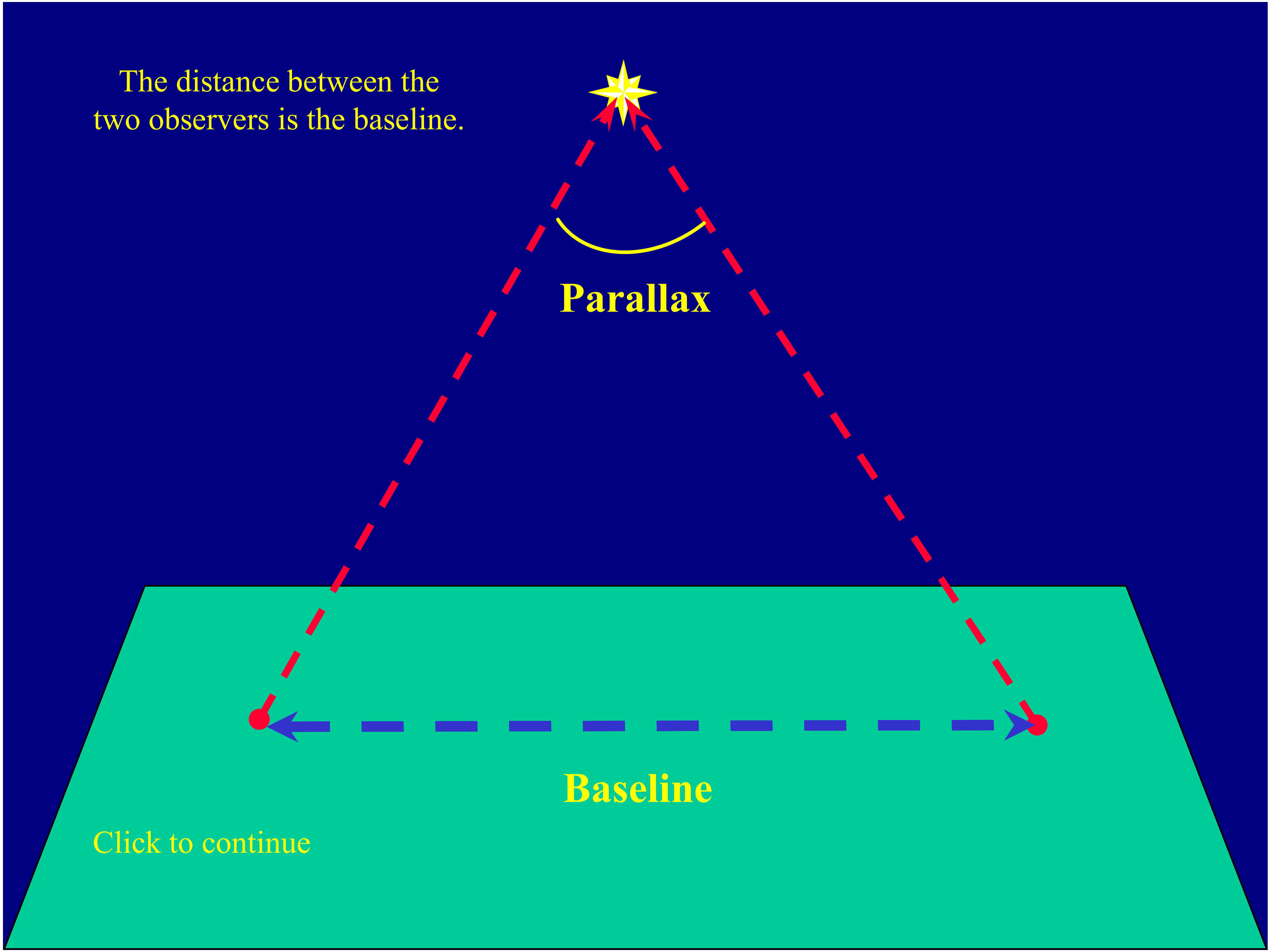

The angle between the
two directions is called . . .
. . . and the method is called
'trigonometric parallax'.
Parallax
Click to continue


The distance between the
two observers is the baseline.
Parallax
Baseline
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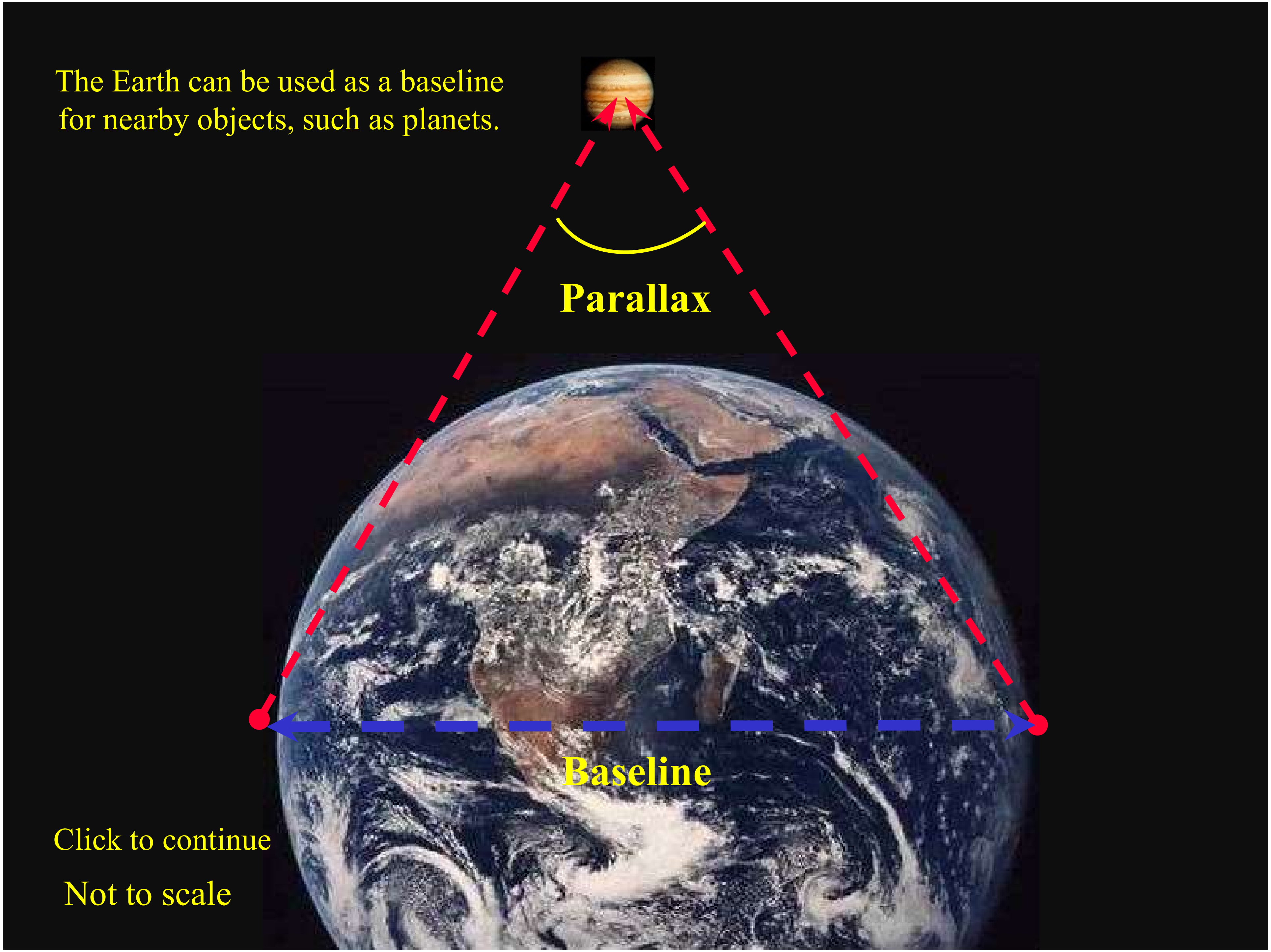
The Earth can be used as a baseline for nearby objects, such as planets.
Parallax
Baseline
Click to continue
Not to scale

In the 17th century, astronomer Edmund Halley suggested that the transit of the planet Venus across the face of the Sun could be used to determine the scale of the solar system.

Click to continue

Transit of Venus, 8 June 2004
(David Le Conte, Guernsey Observatory)

Transit of Venus

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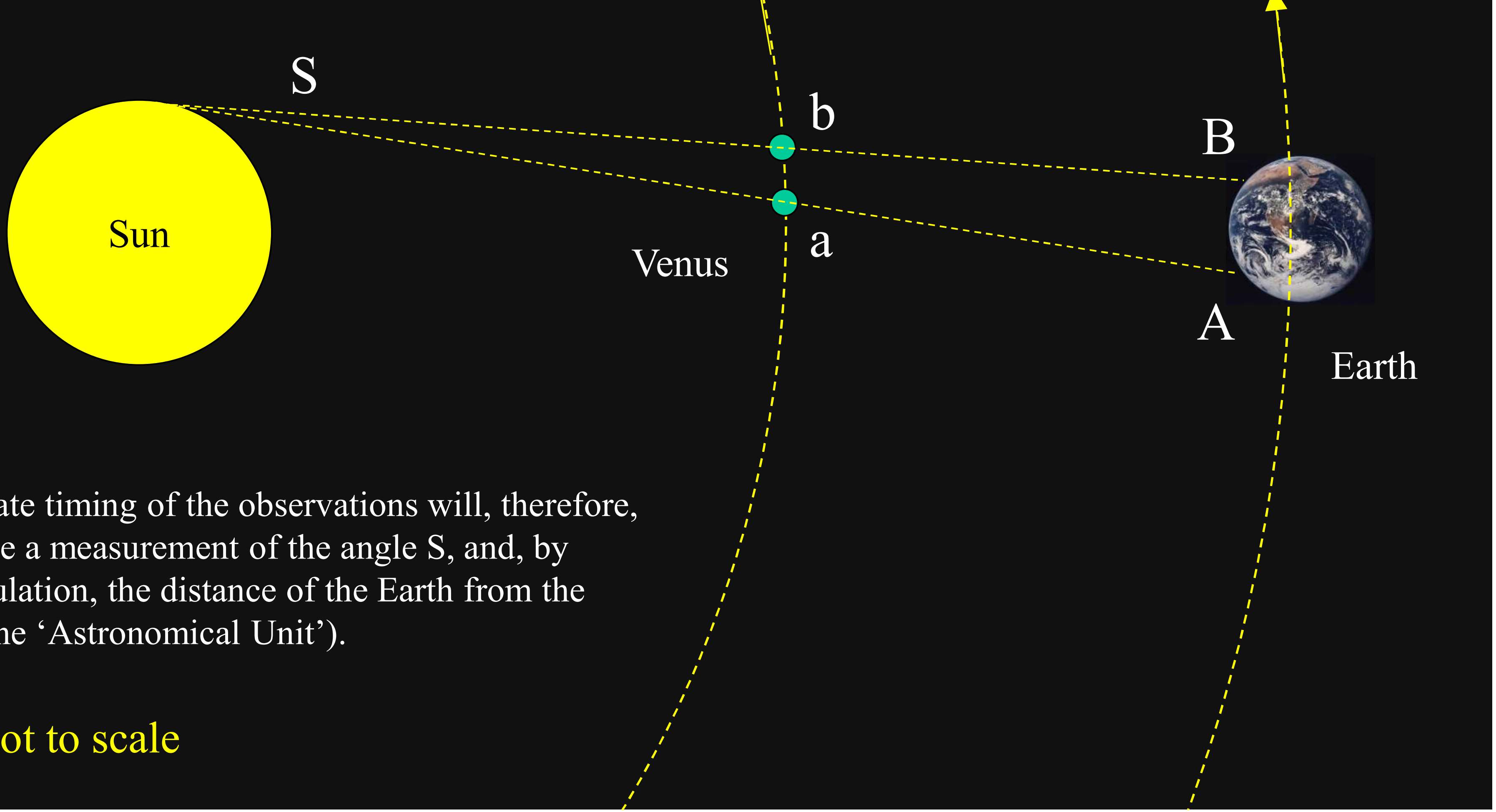
An observer at ‘A’ will observe Venus at the Sun’s limb when Venus is at ‘a’.

An observer at ‘B’ will observe Venus at the Sun’s limb when Venus is at ‘b’.



Accurate timing of the observations will, therefore, provide a measurement of the angle S, and, by triangulation, the distance of the Earth from the Sun (the ‘Astronomical Unit’).

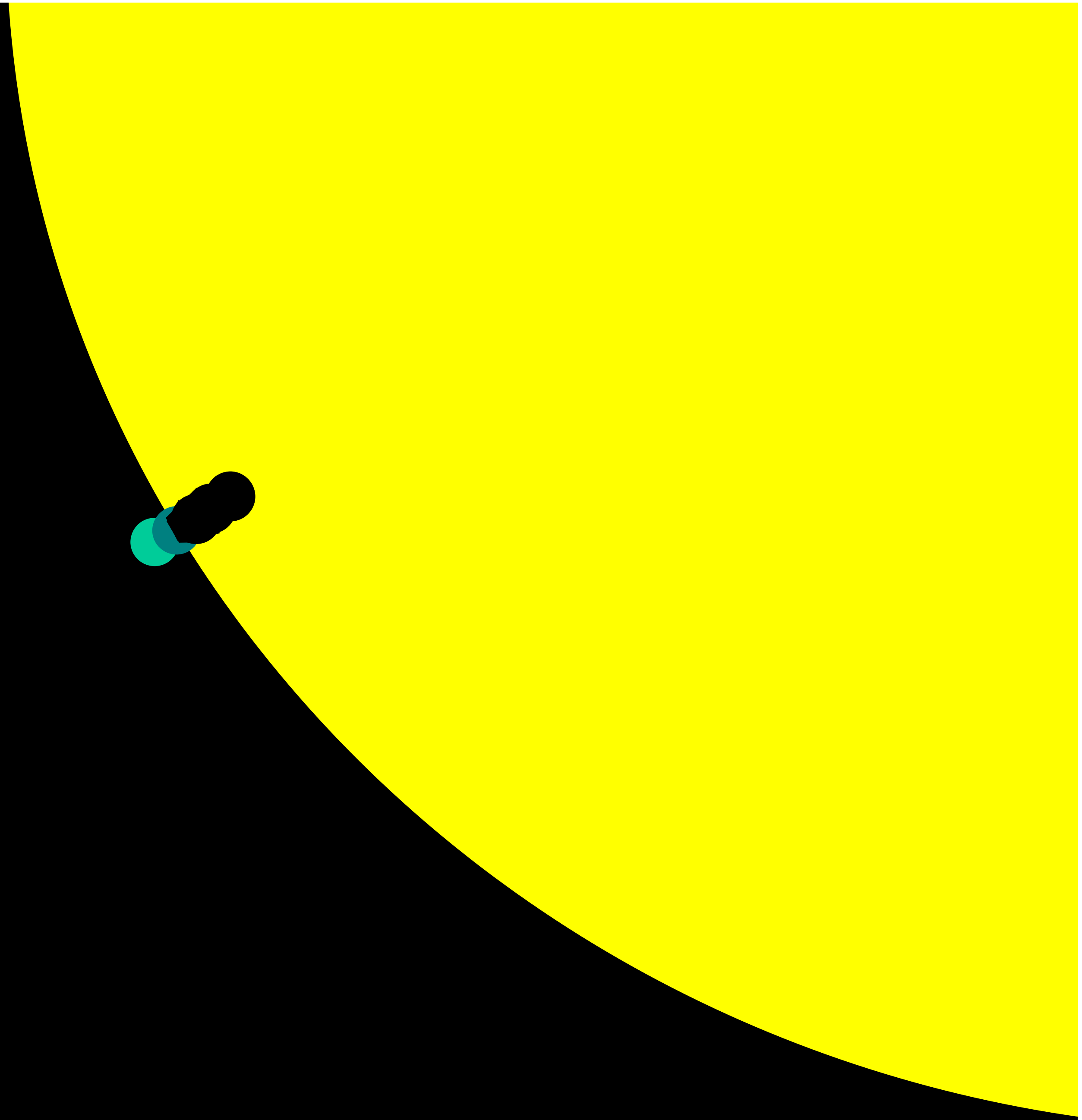
Not to scale

Transit of Venus

In theory the precise time when the edge of Venus crossed the limb of the Sun was to be measured from widely spread locations on the Earth's surface.

In practice, however, observers found it difficult to time the event with sufficient precision because of an effect known as:

- the black drop!



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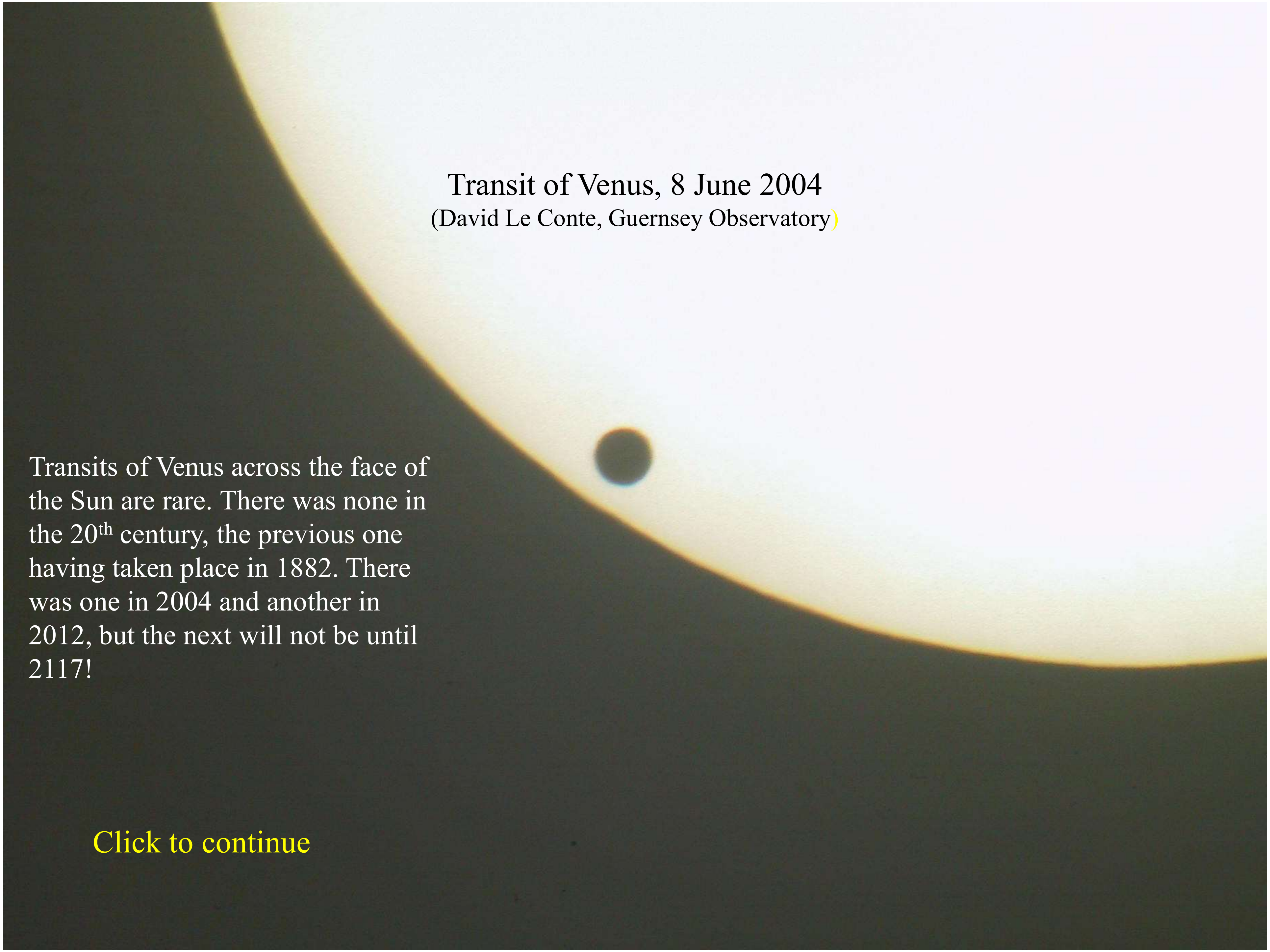
Transit of Venus, 8 June 2004
(David Le Conte, Guernsey Observatory)
Transits of Venus across the face of the Sun are rare. There was none in the 20th century, the previous one having taken place in 1882. There was one in 2004 and another in 2012, but the next will not be until 2117!
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There are now better ways of determining the Astronomical Unit, such as radar. Nevertheless, Halley's method retains an historic interest, and so observers at the Guernsey Observatory took the necessary measurements in 2004 using three independent telescopes.

Results of transit of Venus observations

La Société Guernesiaise Astronomical Observatory

8 June 2004

Average of three independent observers: 149,582,882 km

Accepted value: 149,597,870 km

Difference: 14,988 km (0.01%)

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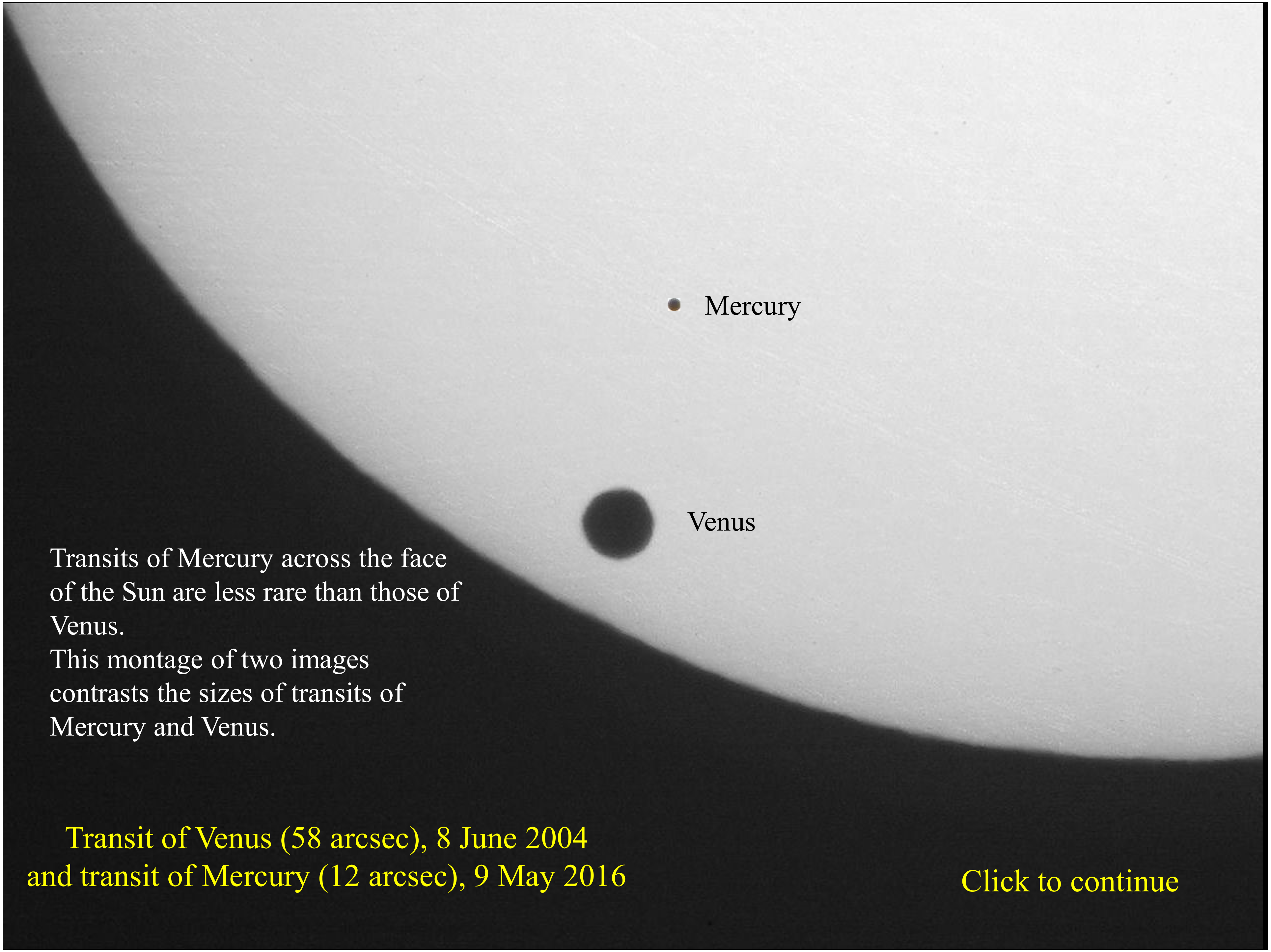
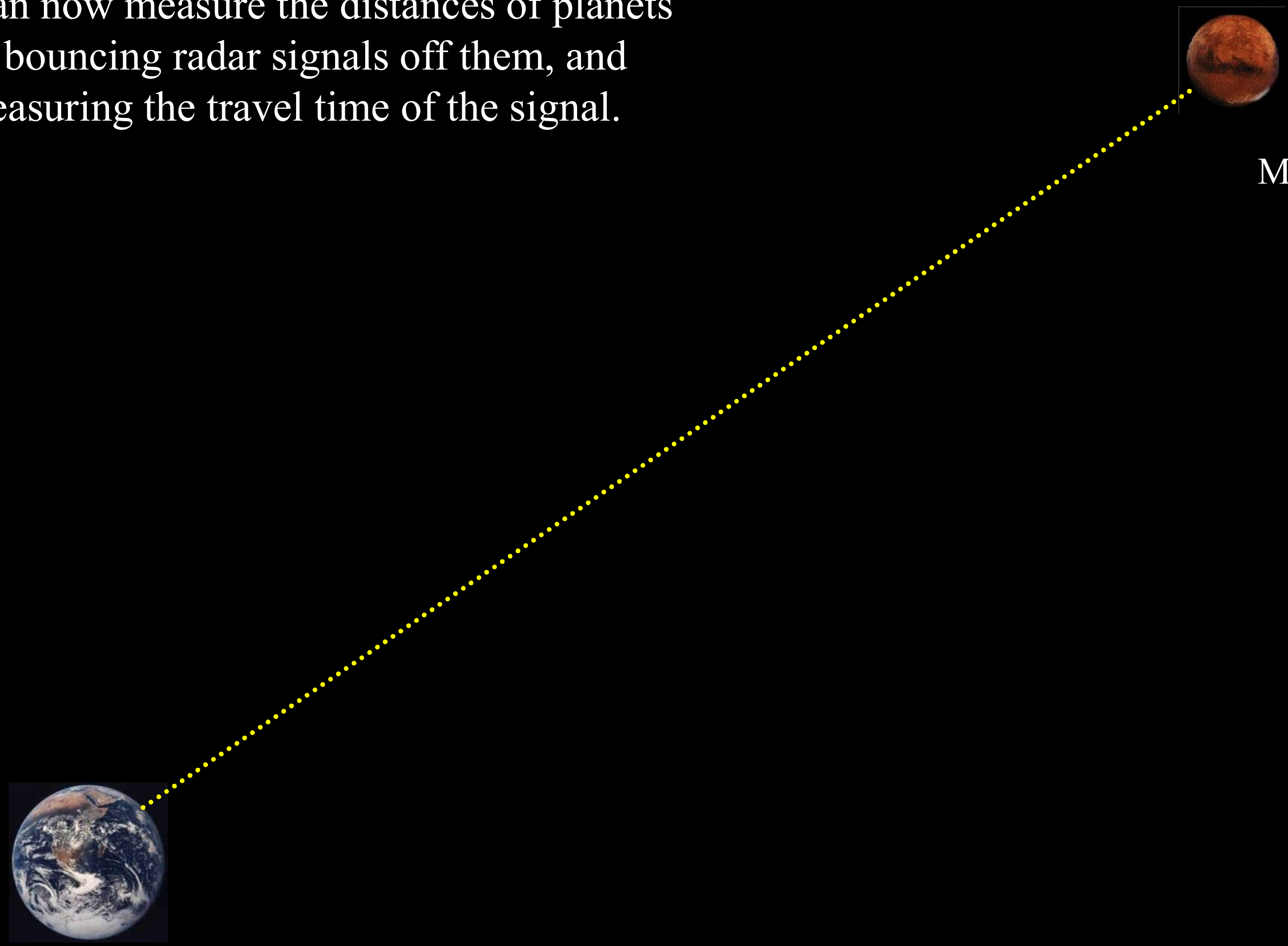

Mercury
Venus
Transits of Mercury across the face of the Sun are less rare than those of Venus.
This montage of two images contrasts the sizes of transits of Mercury and Venus.
Transit of Venus (58 arcsec), 8 June 2004
and transit of Mercury (12 arcsec), 9 May 2016
Click to continue

We can now measure the distances of planets by bouncing radar signals off them, and measuring the travel time of the signal.

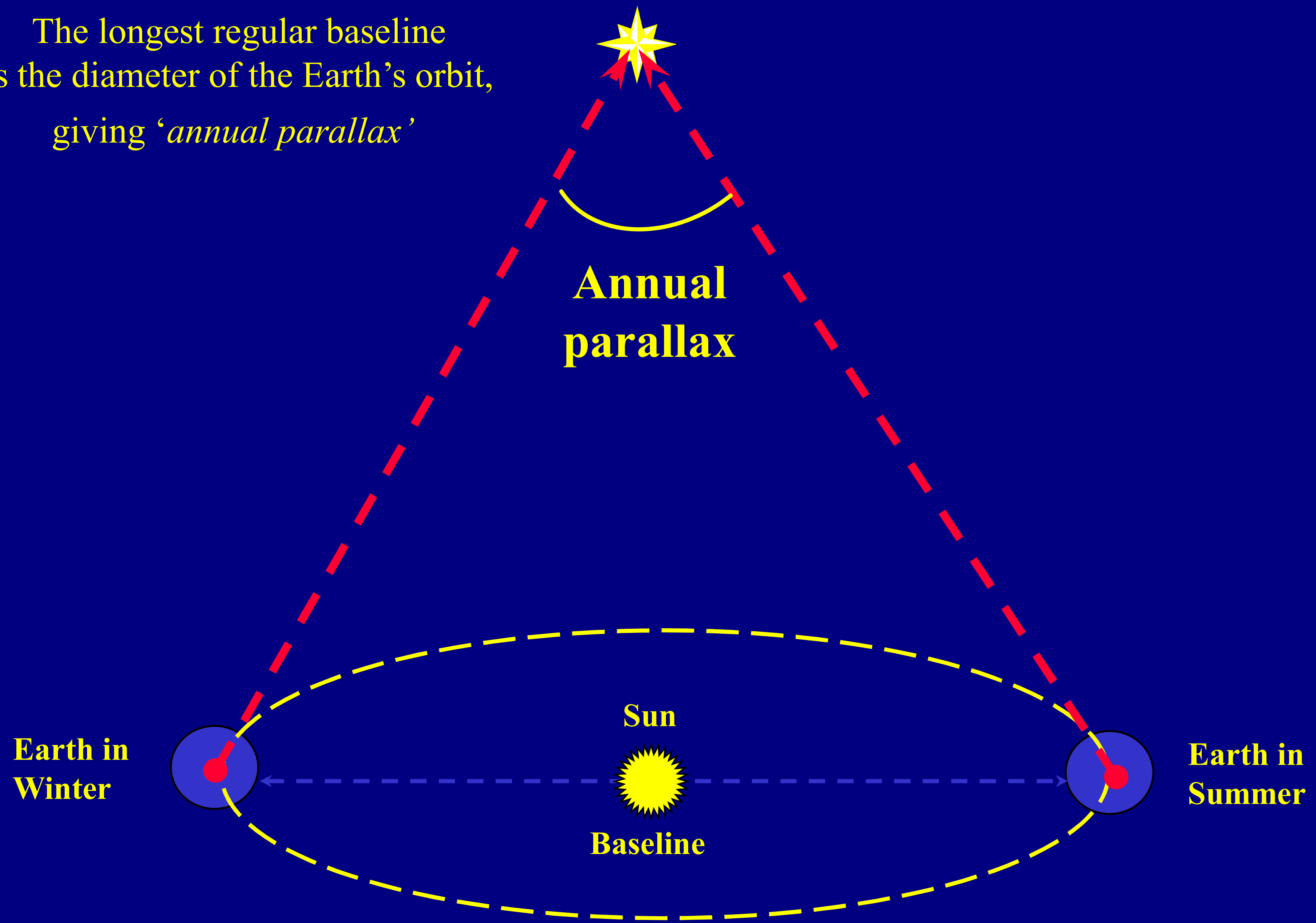


Mars

Earth

Click to continue

The longest regular baseline
is the diameter of the Earth's orbit,
giving '*annual parallax*'



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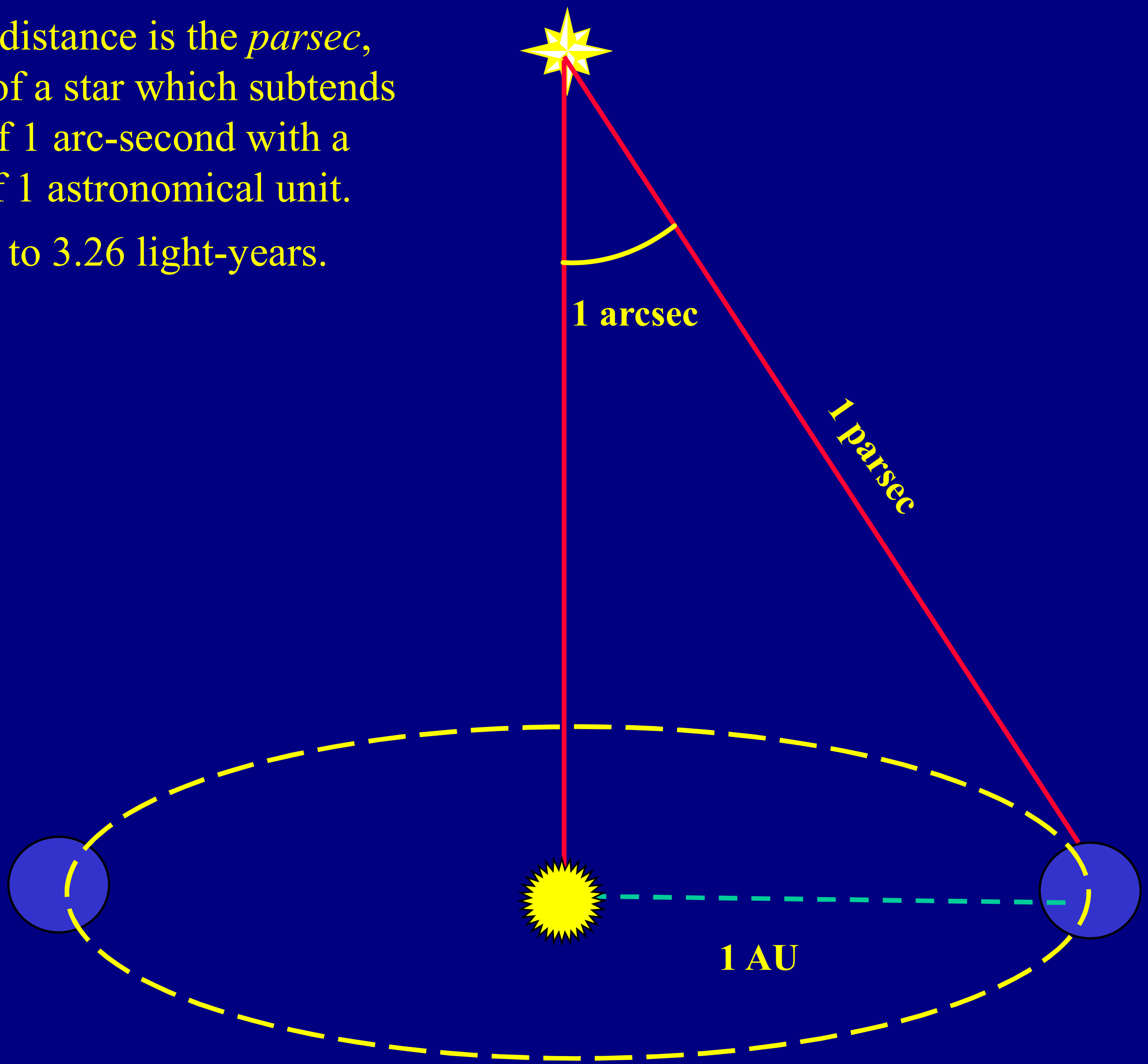
The unit of distance is the *parsec*, the distance of a star which subtends an angle of 1 arc-second with a baseline of 1 astronomical unit.

It is equal to 3.26 light-years.



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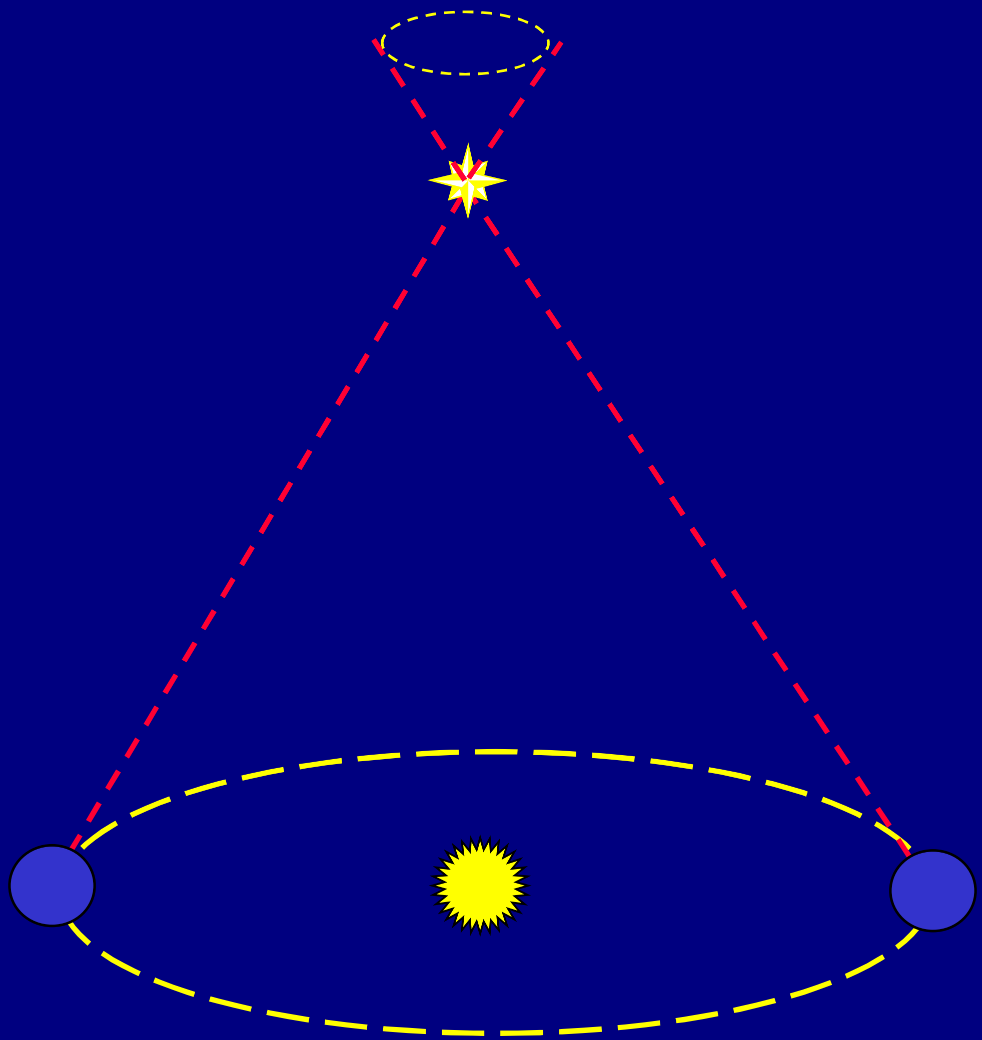
The annual motion of the Earth
makes the star appear to move
in a small ellipse



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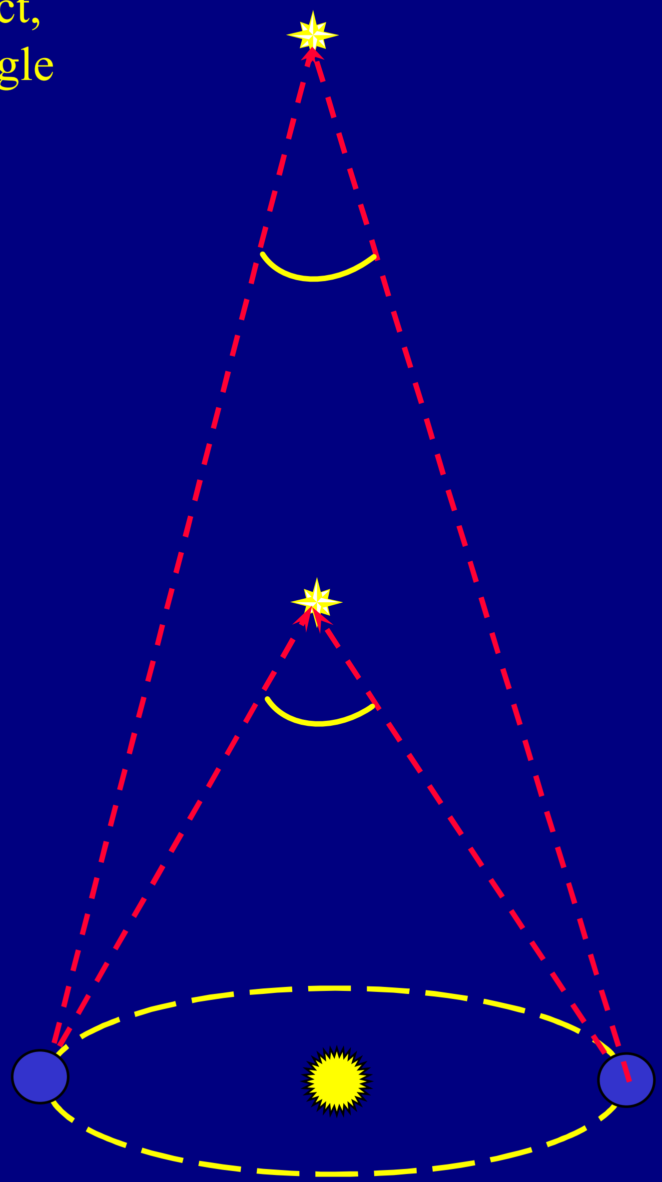
The farther away the object,
the smaller the parallax angle



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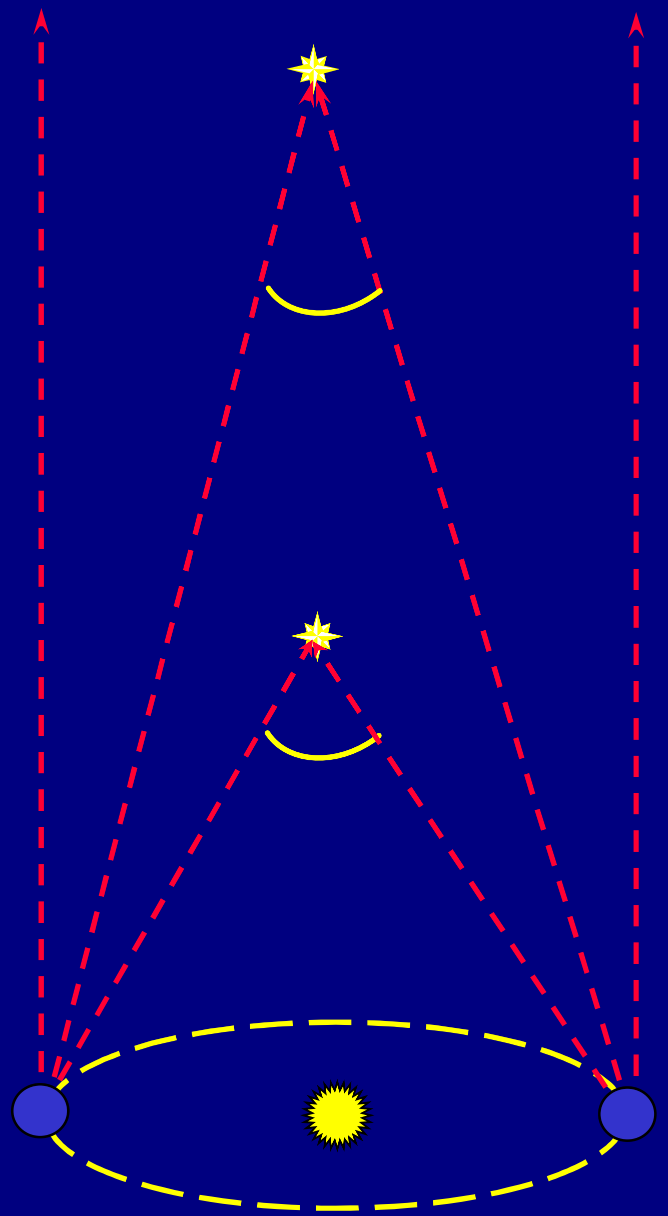
Only nearby stars can be measured in this way; the annual parallax of very distant stars is too small to be measured



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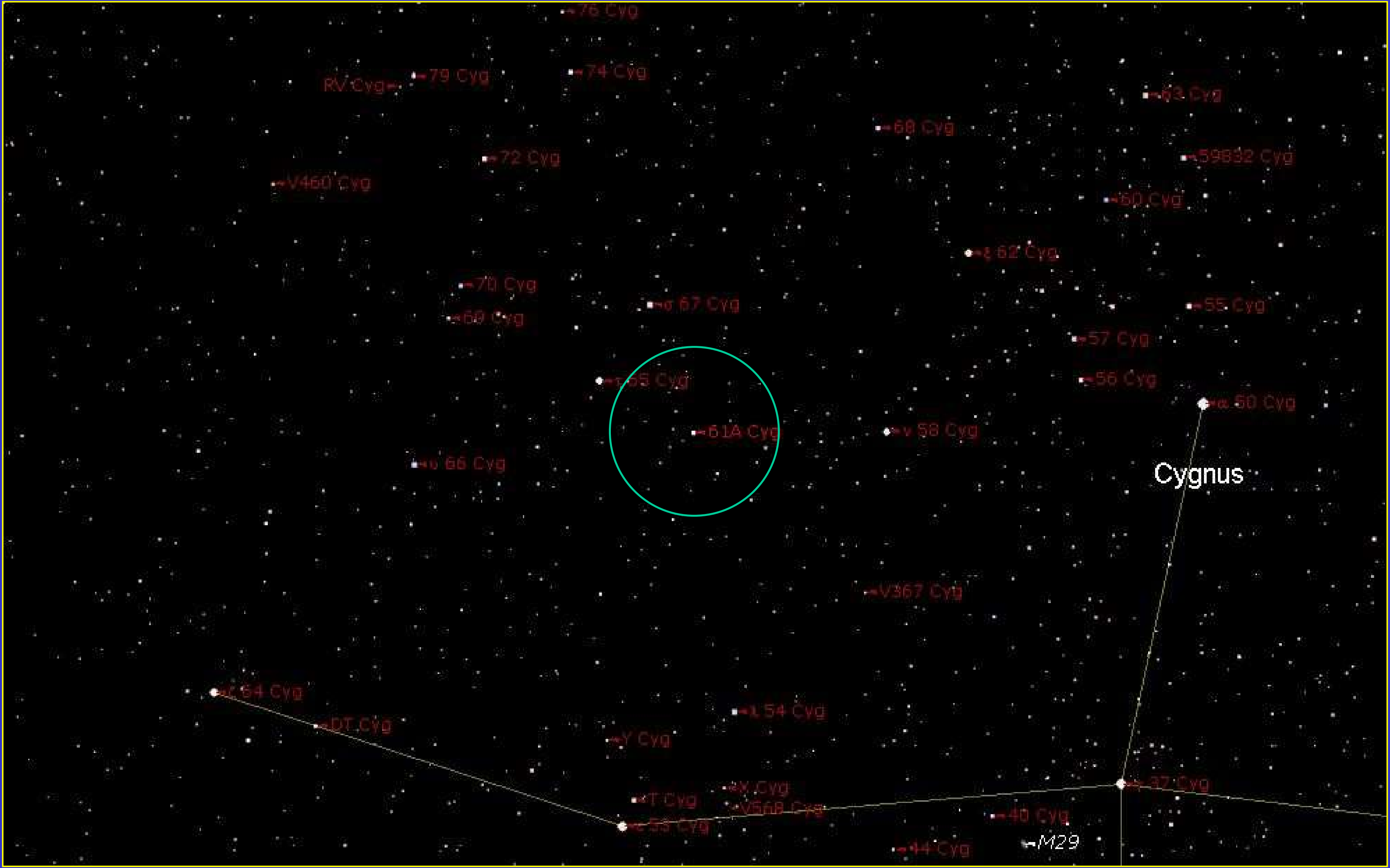
The star 61 Cygni was the first one whose parallax (0.369 arc-seconds) was measured by Friedrich Bessel in 1838, giving a distance of 10.3 light-years.



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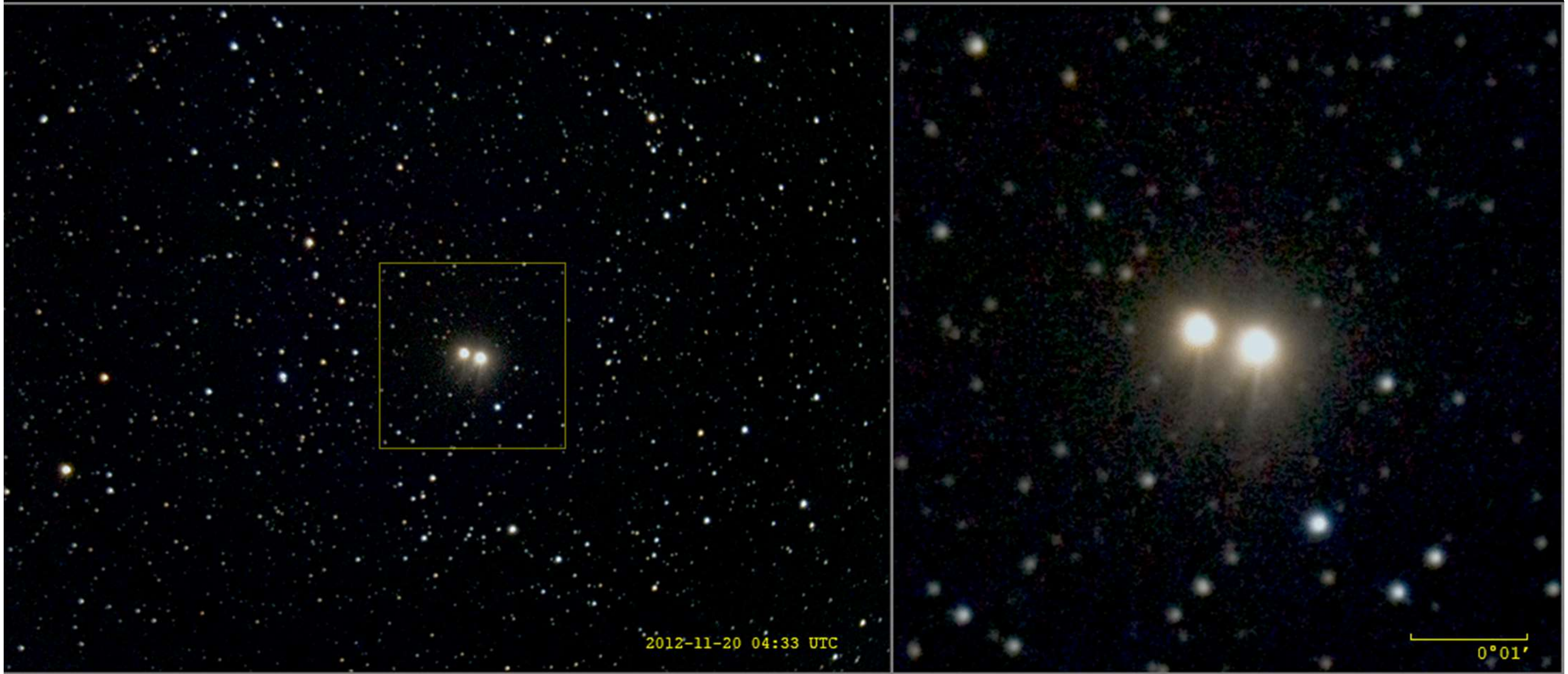
61 Cygni, a double star, is close enough for its motion to be observed.



Proper motion of double star 61 Cygni at one-year intervals

Click to continue

The distance of stars whose parallax can be measured in this way is limited to about 100 parsecs. Here are all stars in the Orion region, to 14th magnitude . . .

Click to continue

. . . and here are the stars in same region, which are within 100 parsecs.

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Distances of open star clusters, such as the Hyades cluster can be determined from the proper motions of stars.

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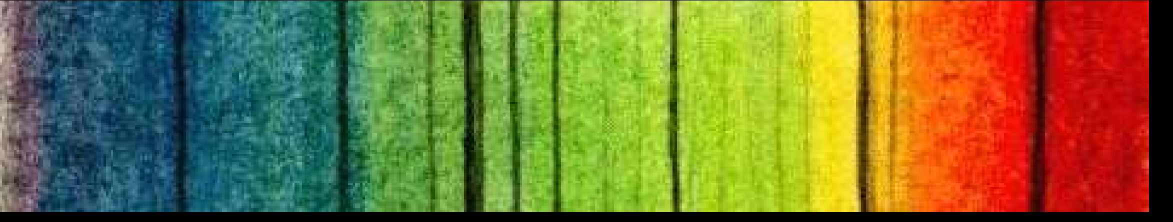
Spectroscopic parallax

This is the spectrum of the star Aldebaran



From such a spectrum we can determine the star’s temperature and surface gravity.

This gives us its mass and luminosity, and therefore its distance.

Click to continue

‘Planetary nebulae’, which are the remains of dead stars, have similar absolute brightnesses, so their distances can be determined from their apparent brightness.

M57 by Daniel Cave, Guernsey Observatory

Click to continue

The distances of globular clusters, which contain hundreds of thousands of stars, can be determined from their brightest stars.

M13 by Matt Skillett, Guernsey Observatory

Click to continue

The brightest stars of nearby galaxies can be resolved and their distances determined as such stars have similar brightnesses.

M81 by Jean Dean, Guernsey Observatory

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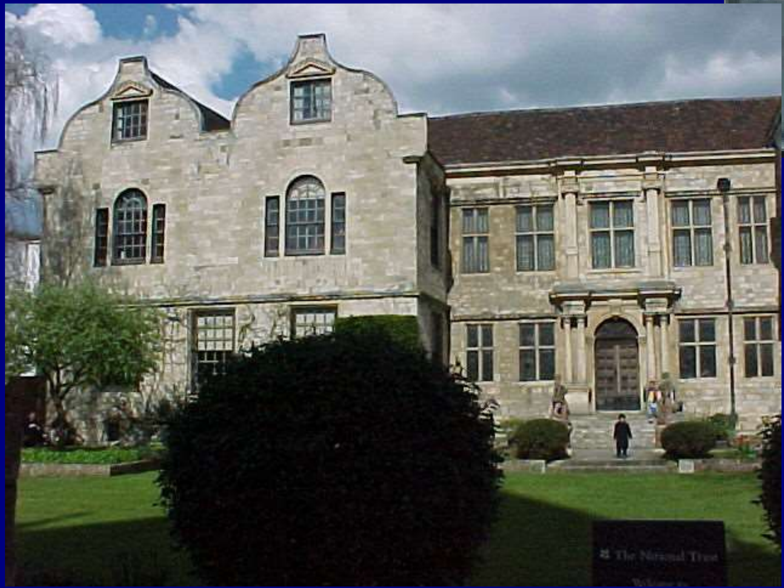
Which brings us back to John Goodricke and his observations of the star δ (delta) Cephei in 1784.



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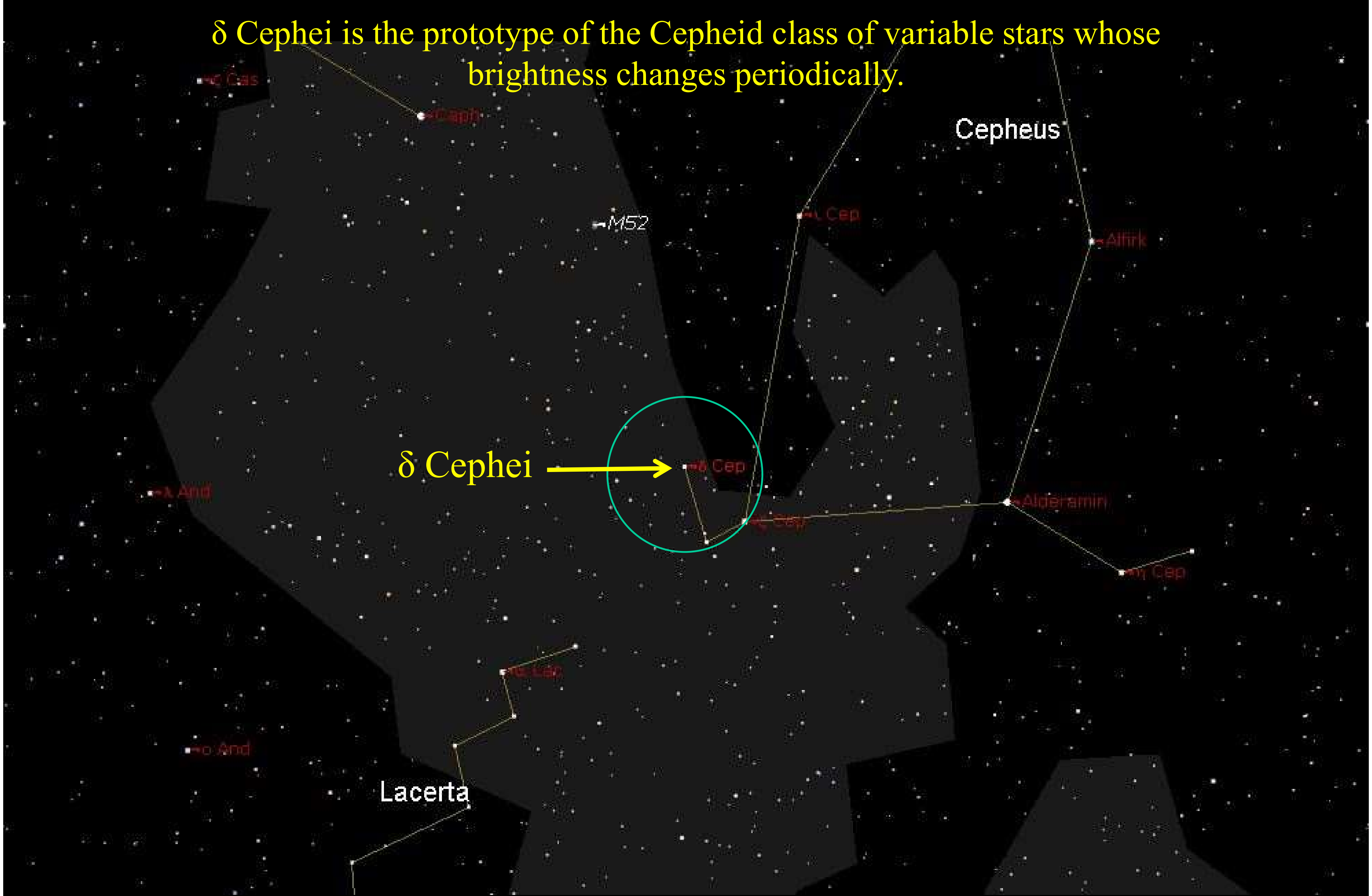
δ Cephei is the prototype of the Cepheid class of variable stars whose brightness changes periodically.



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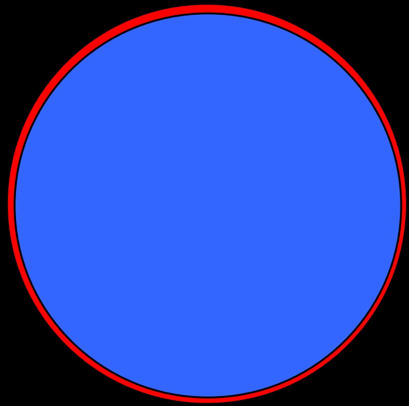
Cepheid variables are all about the same temperature, but pulsate with a periodicity which is dependent on their size and hence their luminosities.



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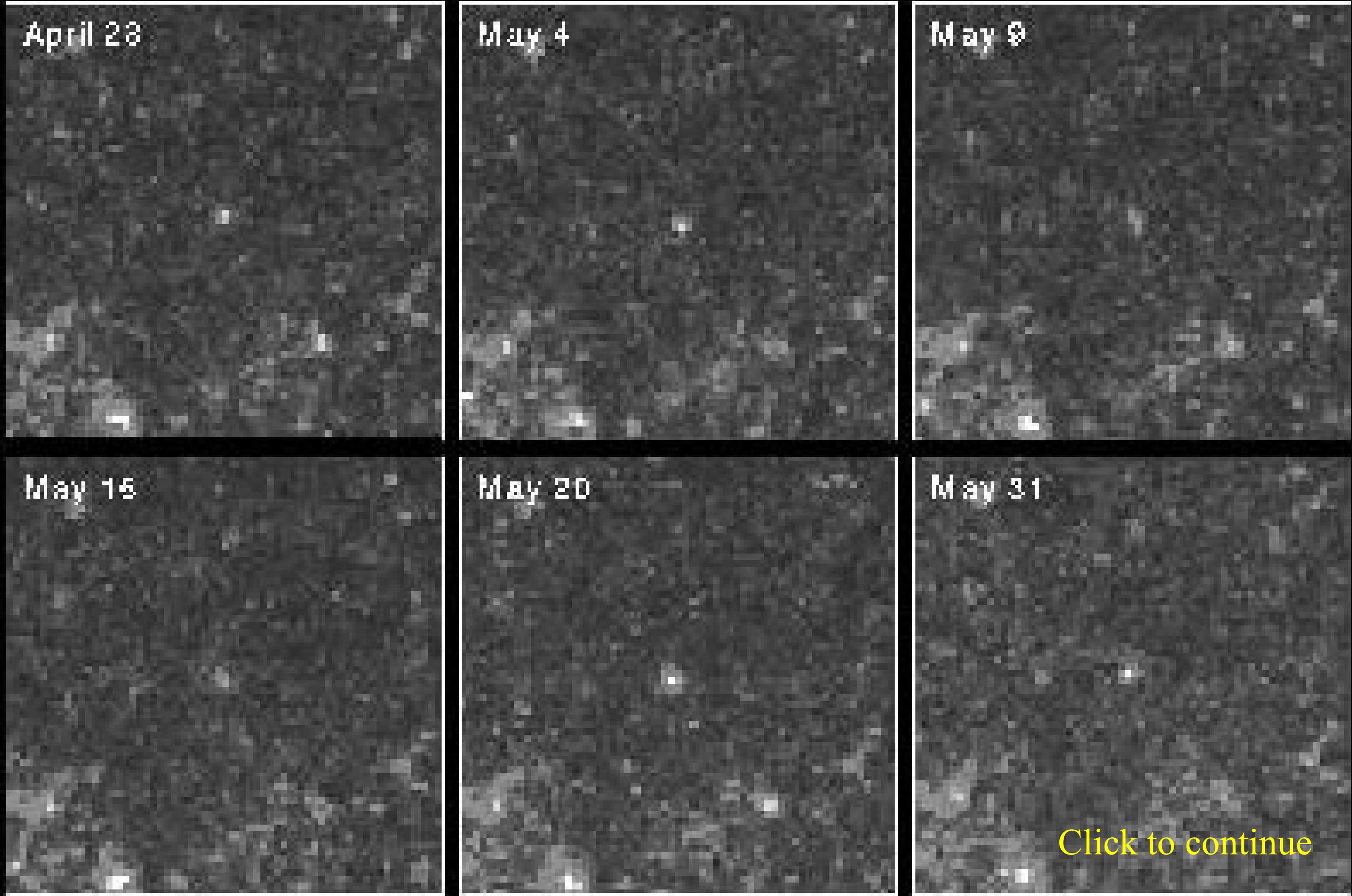
They can be seen in distant galaxies and are, therefore, important for determining galactic distances. Here is a sequence of images of a Cepheid variable in the galaxy M100 showing its variation in brightness over a period of a month.



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Another method is to observe supernovae, very hot stars which explode at the end of their lives, and which have similar luminosities.

Here is one in the galaxy M51, which exploded in July 2005.

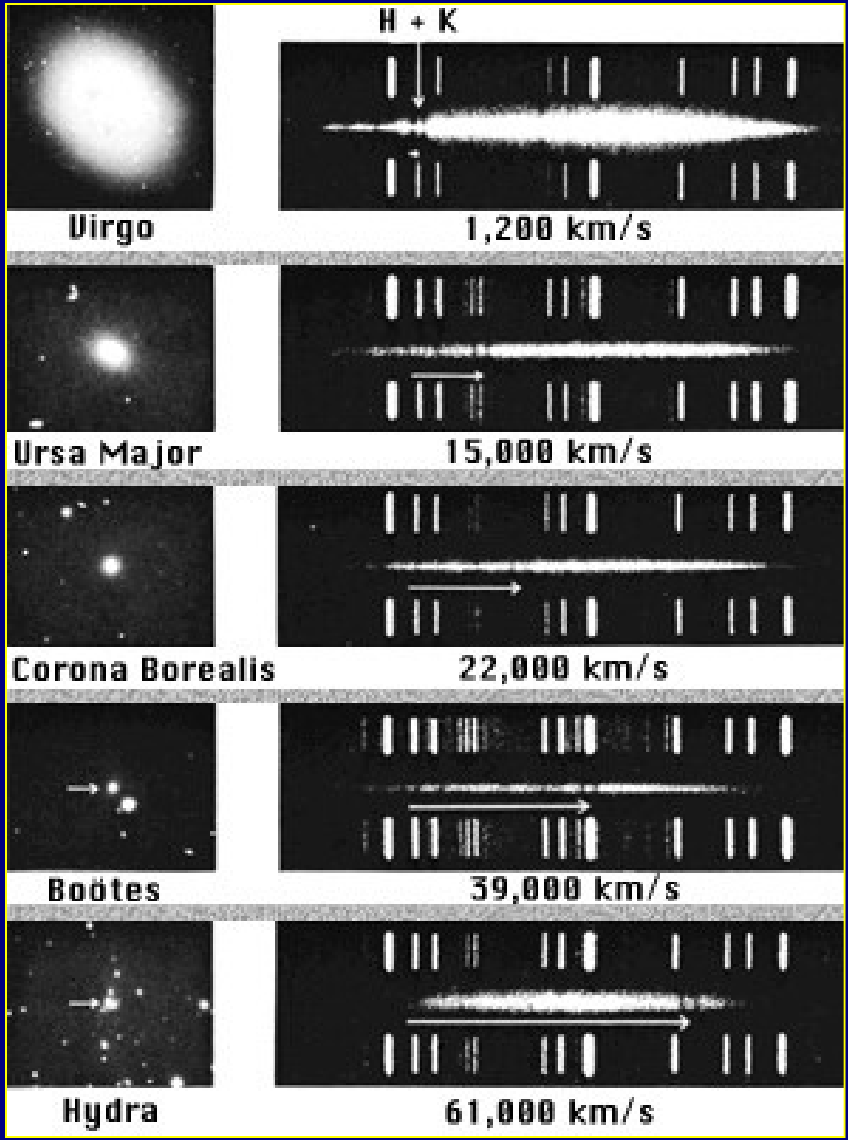
Click to continue

The nearest one in historic times was in the Large Magellanic Cloud in 1987.
It can be seen in these before and after pictures.

Click to continue

The final method, used for very distant galaxies, is based on the redshift of their spectra. This is caused by their recession velocity, which increases with their distance because of the expansion of space.

Here are five galaxies at different distances, together with their recession velocities. The redshift is shown against comparative spectra, the arrows on the spectra indicating the amount of redshift.



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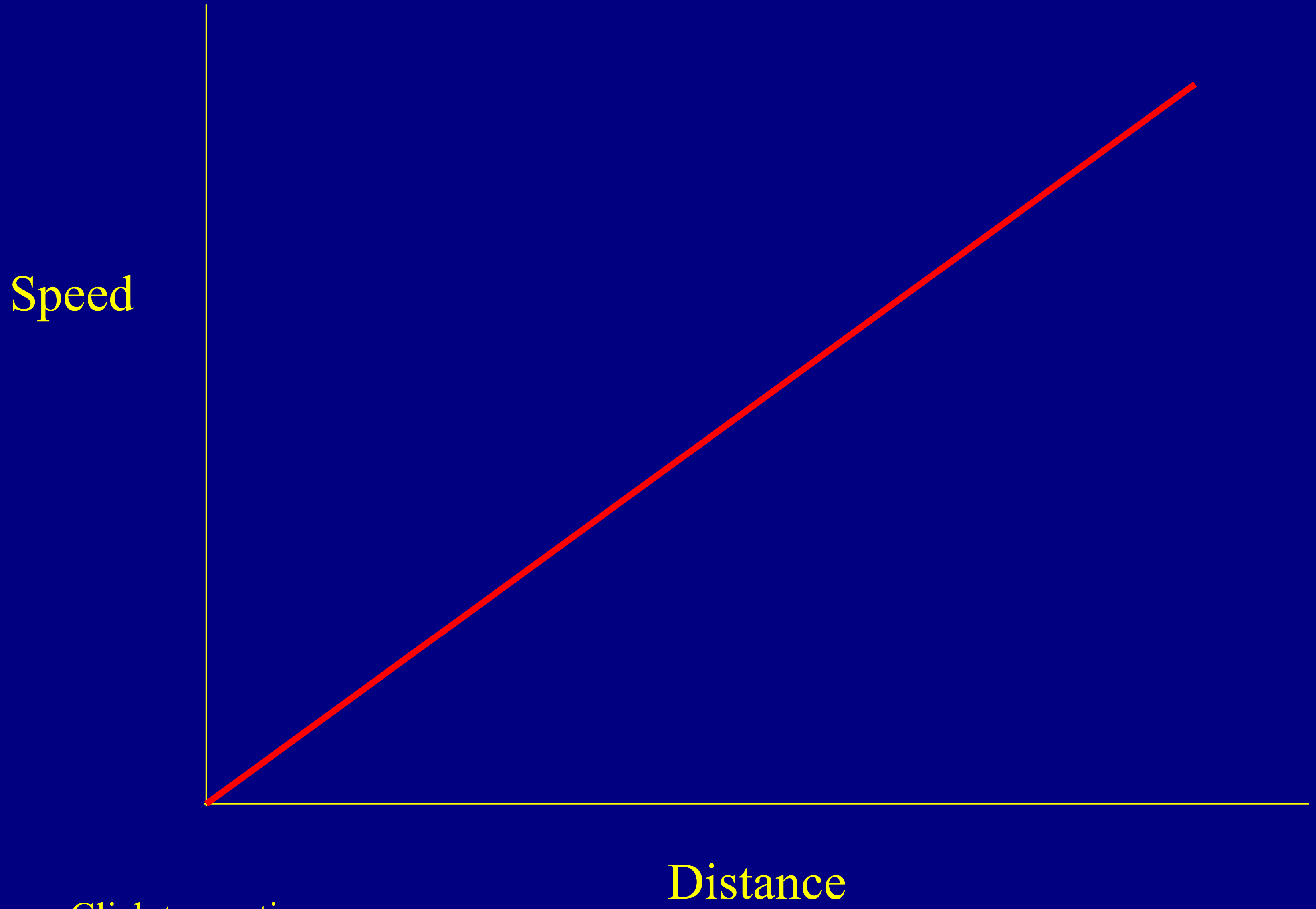
This gives rise to the Hubble Diagram which shows the linear dependence of recession speed of galaxies with their distances.



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So we have a ‘Cosmological Distance Ladder’ of methods of measuring distances, each overlapping with the next.

Hubble Diagram

Supernovae

Cepheid variables

Brightest objects

Main sequence fitting

Spectroscopic parallax

Cluster motions

Trigonometric parallax

Radar

Click to conclude

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