ASTC02 - PROF. HANNO REIN

COSMIC DISTANCE LADDER

ADAPTED FROM SLIDES BY TERENCE TAO (UCLA)

HOW FAR AWAY IS . . .

COSMIC DISTANCE LADDER

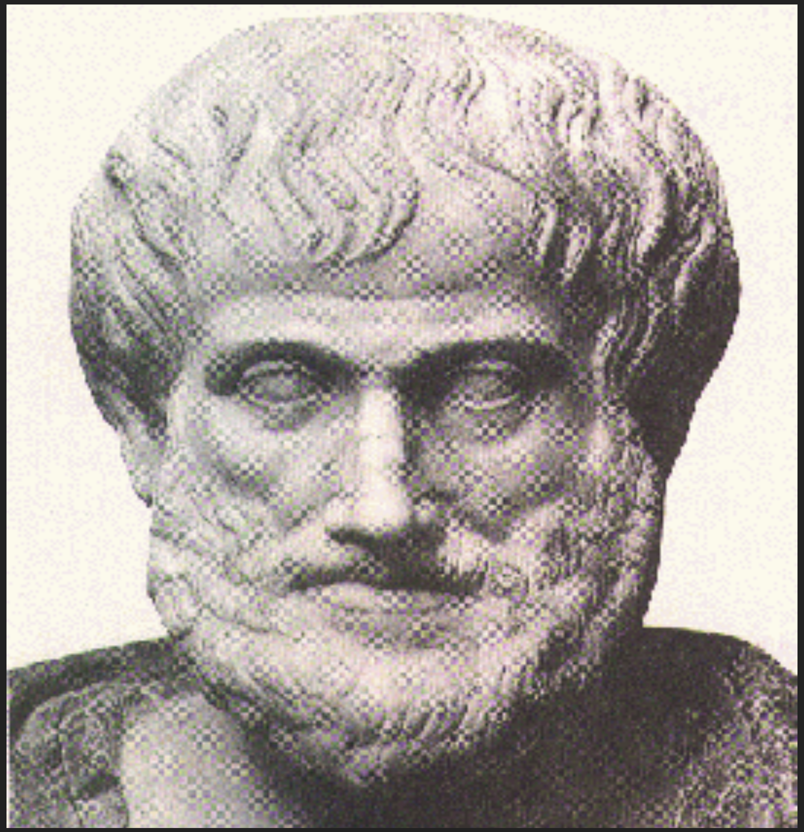
- Work out the answer in steps (rungs)
- Starting with short distances (‘human scale’)
- Calibrate each rung using the previous one
- Ending with distances comparable to the size of the observable universe

9 RUNGS

RUNG 1 – RADIUS OF THE EARTH

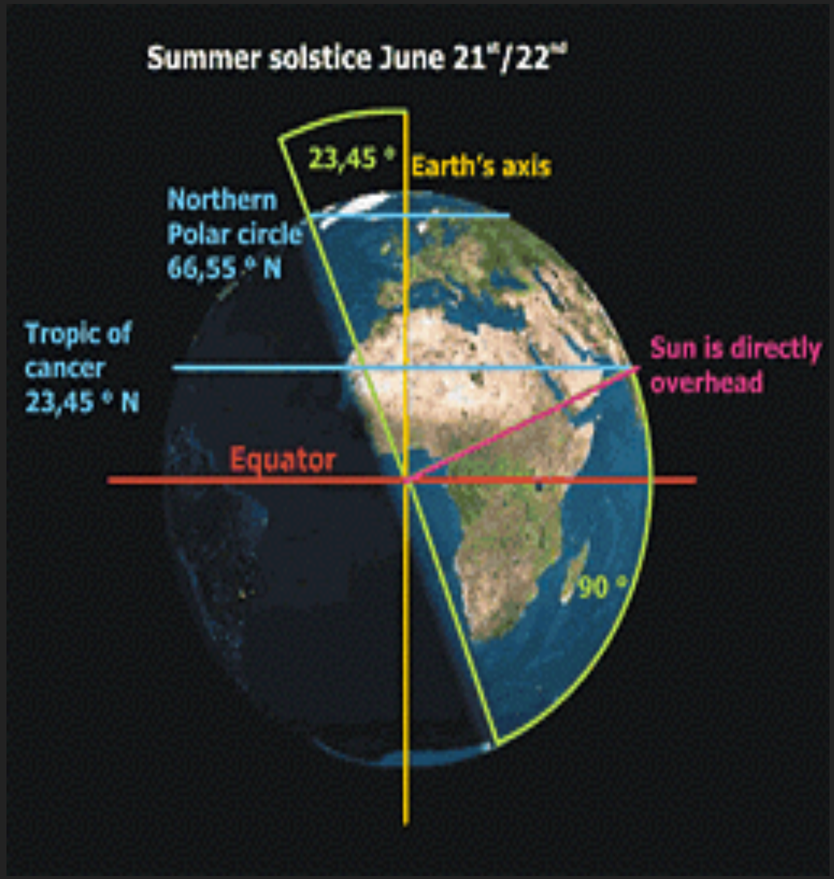
ARISTOTLE 384-322 BCE

- Sun is alway opposite of moon during lunar eclipses
- Must be caused by Earth's shadow
- Terminator always a circular arc, independent of the position of the Earth and Sun
- Only one object whose projection is always a circle: a sphere.



ERATOSTHENES 276-194 BCE

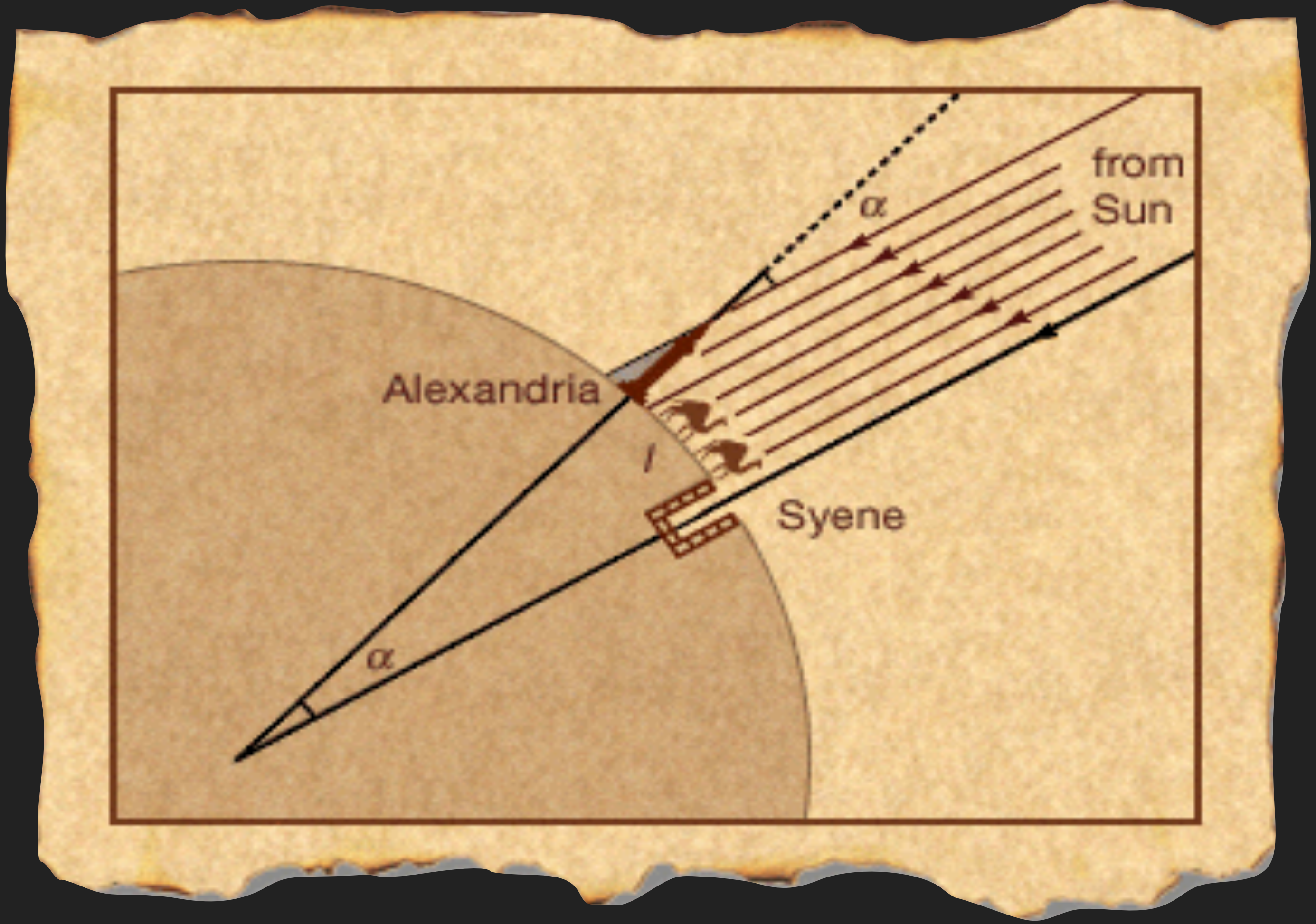
- Aristoteles already knew that Earth can't be incredibly large: some stars can be seen from Egypt but not from Greece
- A well in Syene, Egypt reflects sun light at noon on June 21
- A well in Eratosthenes' hometown, Alexandria did not reflect the Sun.
- Sun was at a 7 degree angle.
- Once we know the distance between Alexandria and Syene, we know the radius of the Earth!



ERATOSTHENES

276-194 BCE

- Distance between Alexandria and Syene estimates to be 5000 stadia (740 km).
- Used information from trade caravans for the estimate!
- Result: 40,000 stadia (about 6800 km)
- Only 8% off!



RUNG 2 - RADIUS AND DISTANCE OF THE MOON

ARISTARCHUS 310-230 BCE

- Knew lunar eclipses caused by shadow of Earth
- Shadow size roughly 2 Earth radii
- Many observations show that eclipses take roughly 3 hours
- Moon takes one month to make a full rotation around the Earth
- What is the distance?
- Distance to the moon about 60 Earth radii

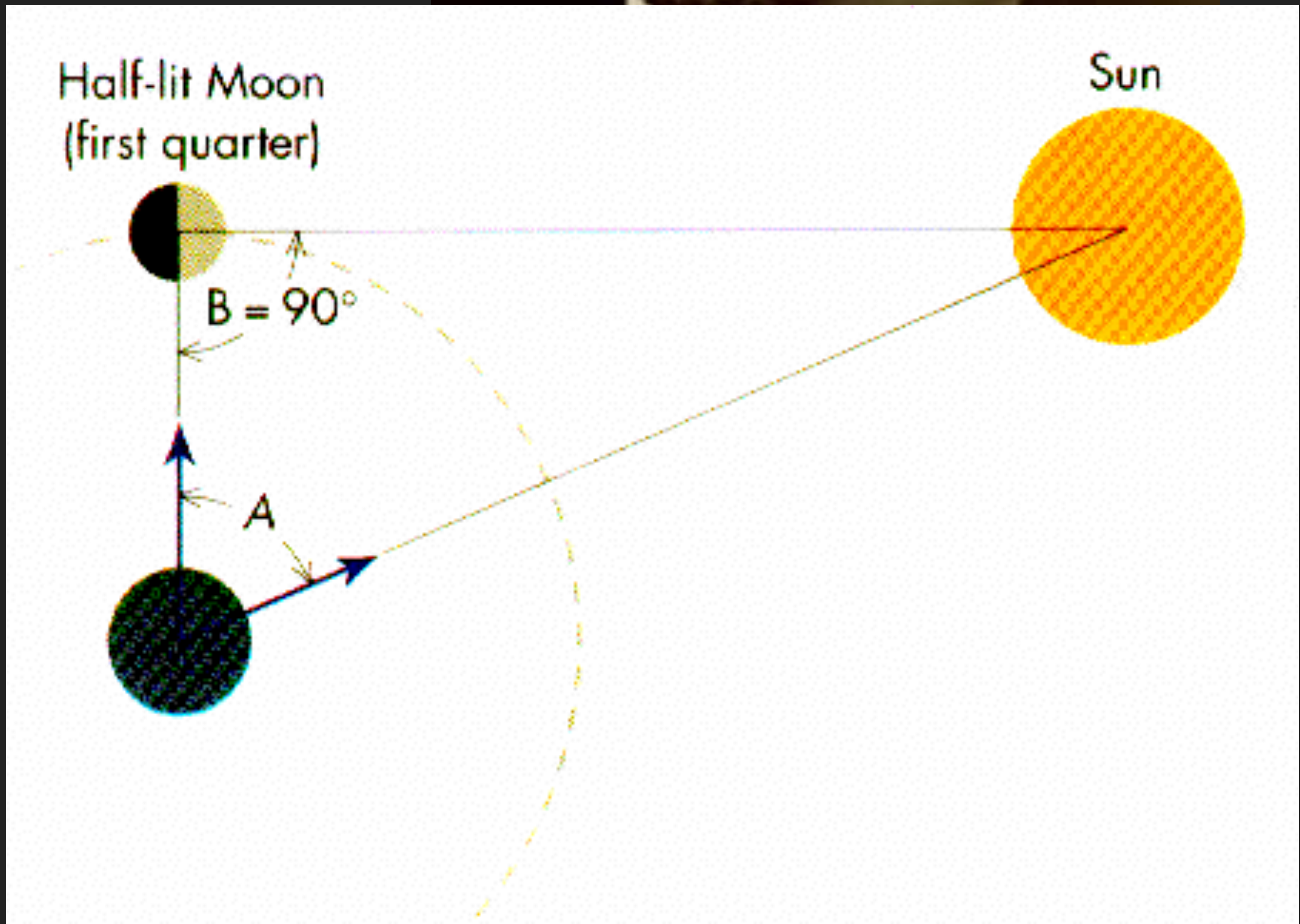
ARISTARCHUS 310-230 BCE

- Have: distance to the Moon.
- Still need: angular size. Idea: measure the time it takes to set.
- 2 minutes = 1/720 of a day
- 1/720 of 360° = 0.5°
- Basic trigonometry gives the radius of the Moon (1/3 Earth's radius)
- Side problem: Aristarchus did not have an accurate value of π!

RUNG 3 – RADIUS AND DISTANCE OF THE SUN

ARISTARCHUS 310-230 BCE

- Each new Moon appears one lunar month after the previous one
- Aristarchus noticed that a half Moon occurs slightly earlier than the midpoint between a new and a full Moon.
- He estimated 12 hours.
- But is hard to measure precisely.
- True value: 1/2 hour
- Elementary trigonometry gives the distance to the Sun!



HIPPARCHUS 190-120 BCE
PTOLEMY 90-168 CE

- Because of this difficulty, Aristarchus estimates the distance to the Sun to be 20 times the distance Earth-Moon
- Hipparchus and Ptolemy improves the result to 42
- True value is 390
- But important conclusion:
  Sun is much further away!
- Heliocentric model (1700 years before Copernicus)

RUNG 4 – DISTANCES FROM THE SUN TO THE PLANETS

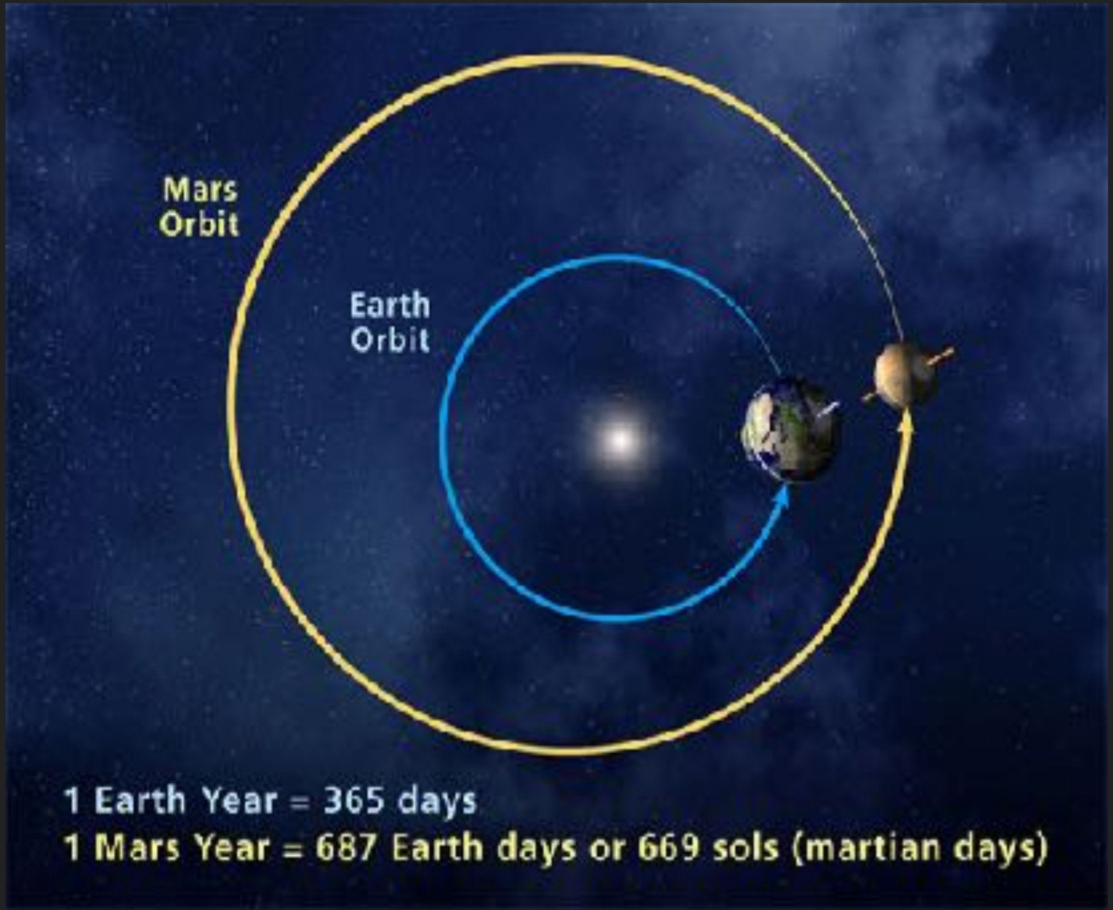
BABYLONIANS

- Already knew the apparent motion of Mars repeats itself after 780 days
- Called the synodic period

PTOLEMY

90-168 CE

- Calculation of the distance to Mars already attempted by Ptolemy
- Got inaccurate results because of the error in the Earth-Sun distance:
  Sidereal period of 15 years
  Distance of 4.1 AU
- True values are 687 days and 1.5 AU



COPERNICUS

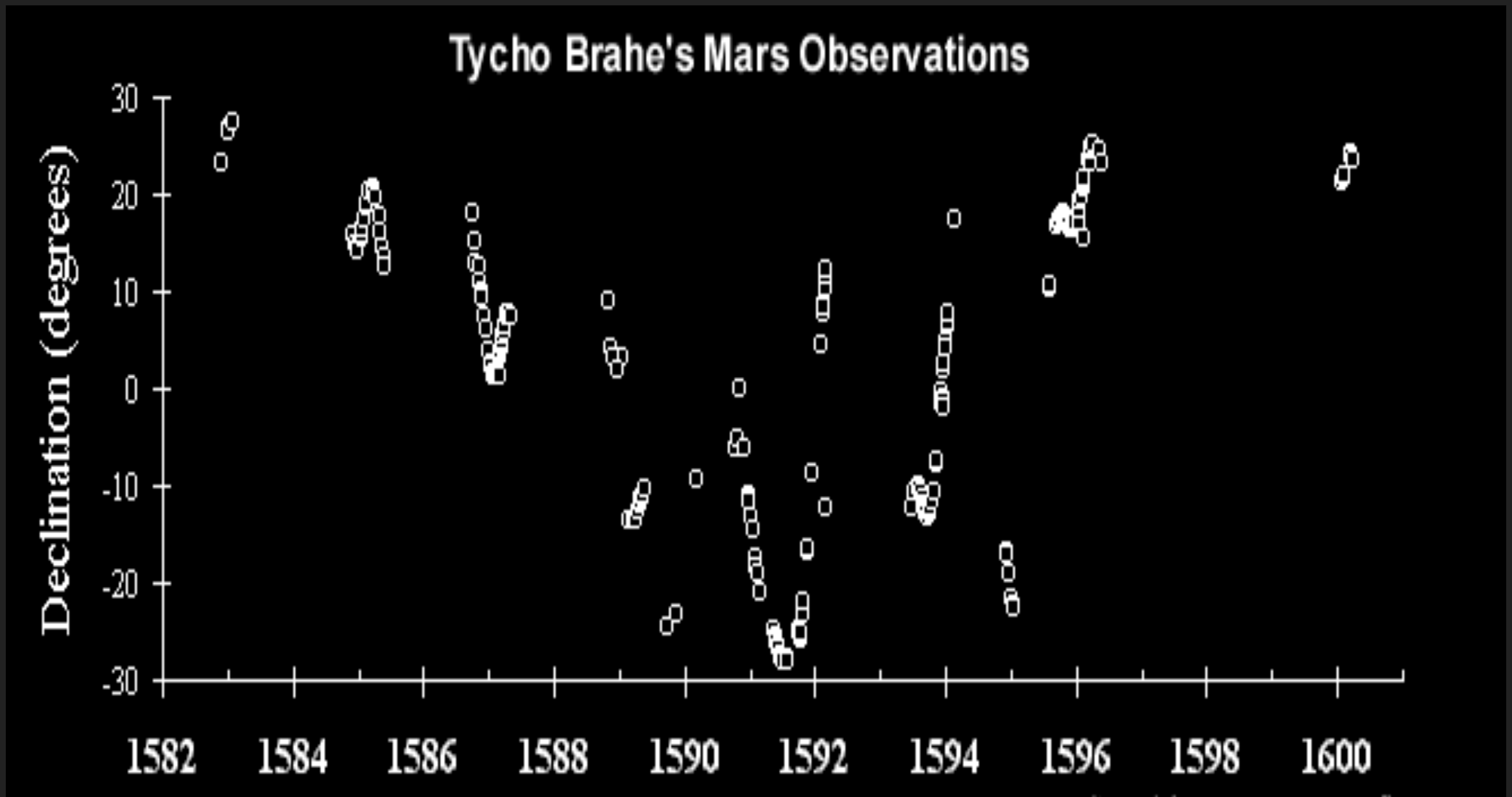
1473-1543

- Know synodic period of 780 days
- Copernican model asserts that Earth revolves around Sun in 365 days
- Subtract the two angular velocities to get the Martian sidereal period of 687 days

KEPLER

1571-1630

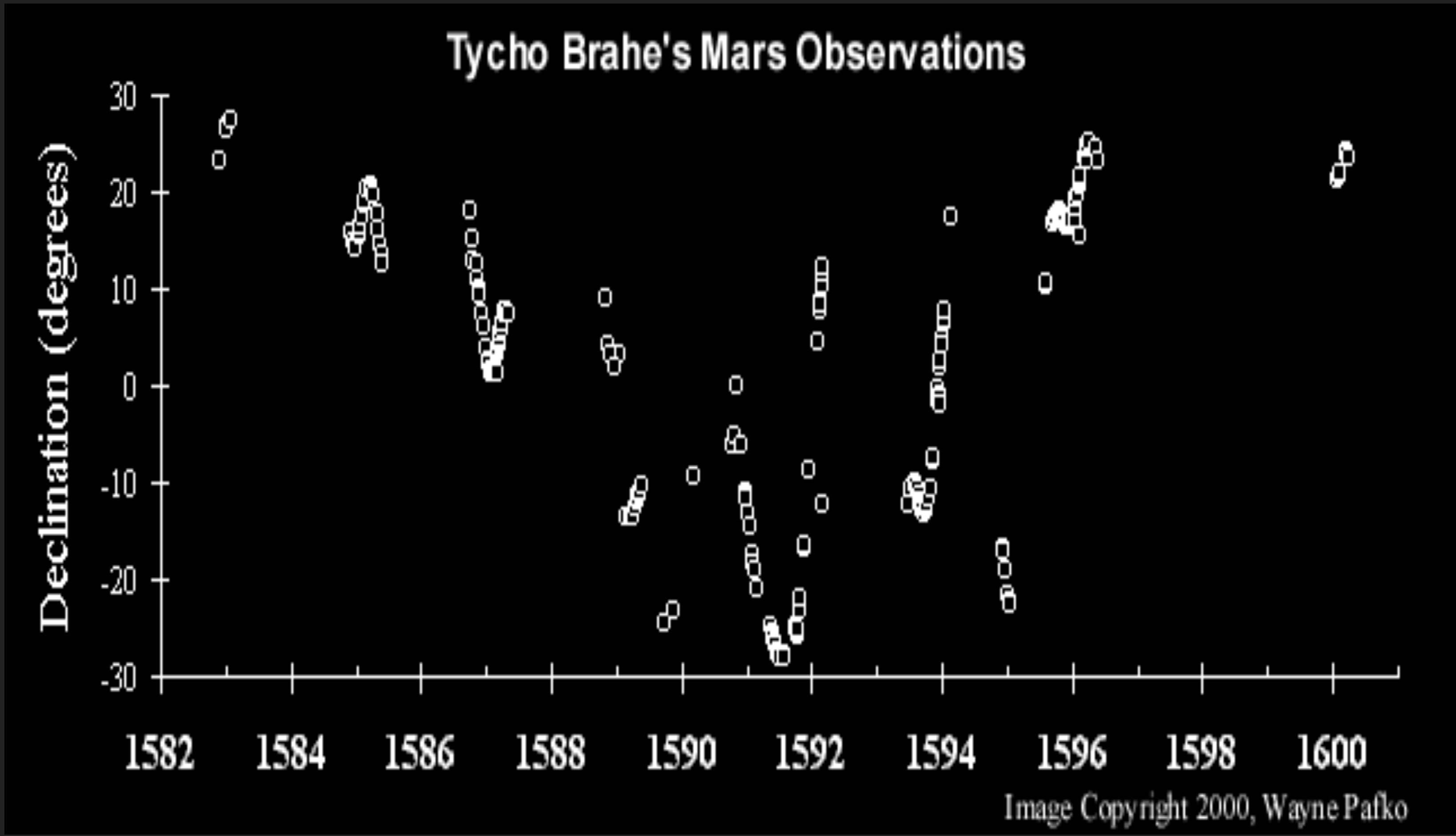
- Copernicus assumes planets move in perfect circles
- Kepler suspected that was not the case
- Did not match Tycho Brahe’s observations



KEPLER

1571-1630

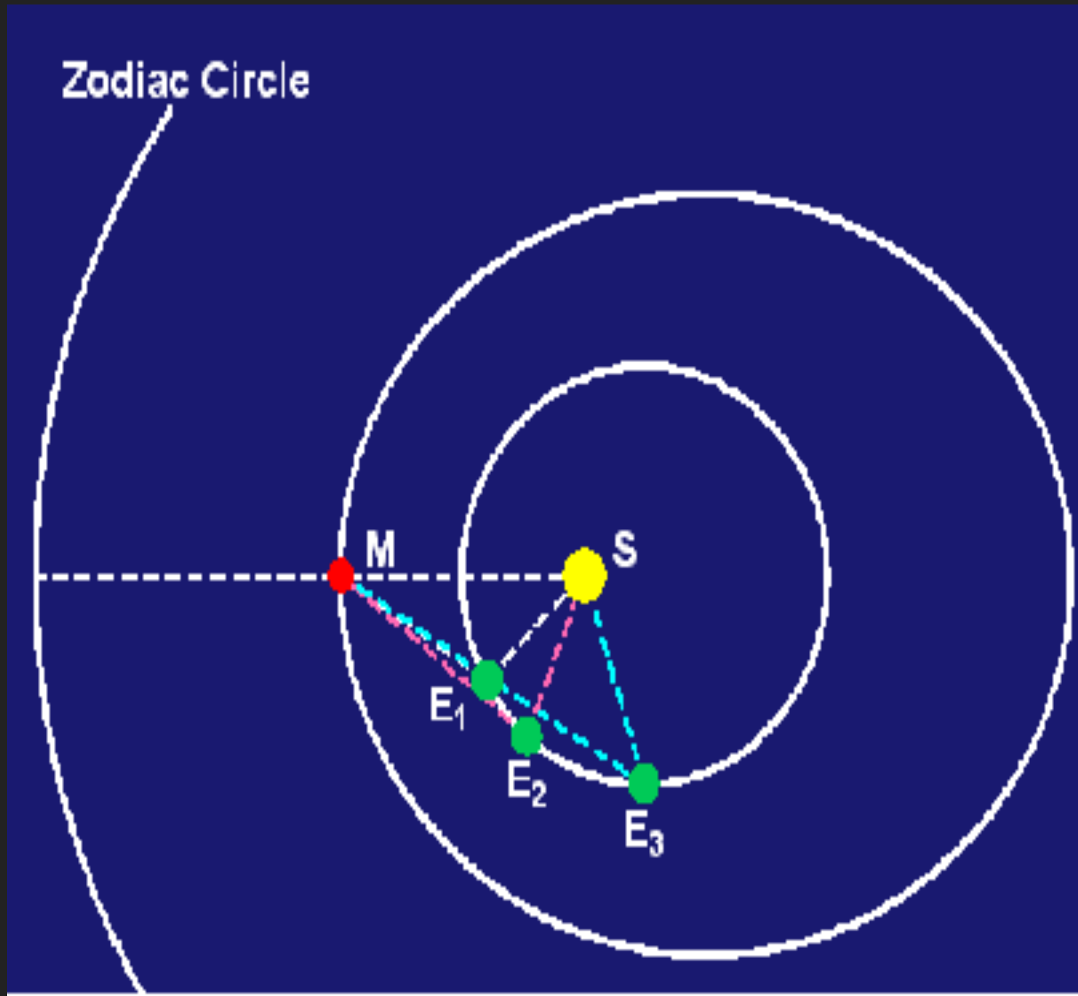
- Calculating the orbit exactly from these observations seemed hopeless - not enough information
- To find the orbit, we need to know Earth's location first (see your lab report for finding asteroid orbits)
- But how can we observe the Earth if we're on it?
- Chicken and egg problem



KEPLER

1571-1630

- Einstein called Kepler's trick *an idea of pure genius.*
- Use Mars itself as a fixed point of reference to observe Earth!
- Take measurements spaced 687 days apart
- Mars will be at exact same location
- Earth will have moved
- Can now determine Earth's orbit from fixed point of reference!



RUNG 5 – SPEED OF LIGHT

RØMER

1644-1710

- Speed of light can be measured in the lab nowadays.
- First measurement used astronomy
- Rømer observed Io rotating around Jupiter evert 42.5 hours.
- Can be timed exactly by the time moon enters planet's shadow.

RØMER

1644-1710

- Noticed that period is not uniform depending on relative position of Earth and Jupiter
- When Earth moves away from alignment with Jupiter, period lagged by about 20 minutes.
- Conclusion light needs 20 minutes to travel
2 AU
- True value 17 minutes

RØMER

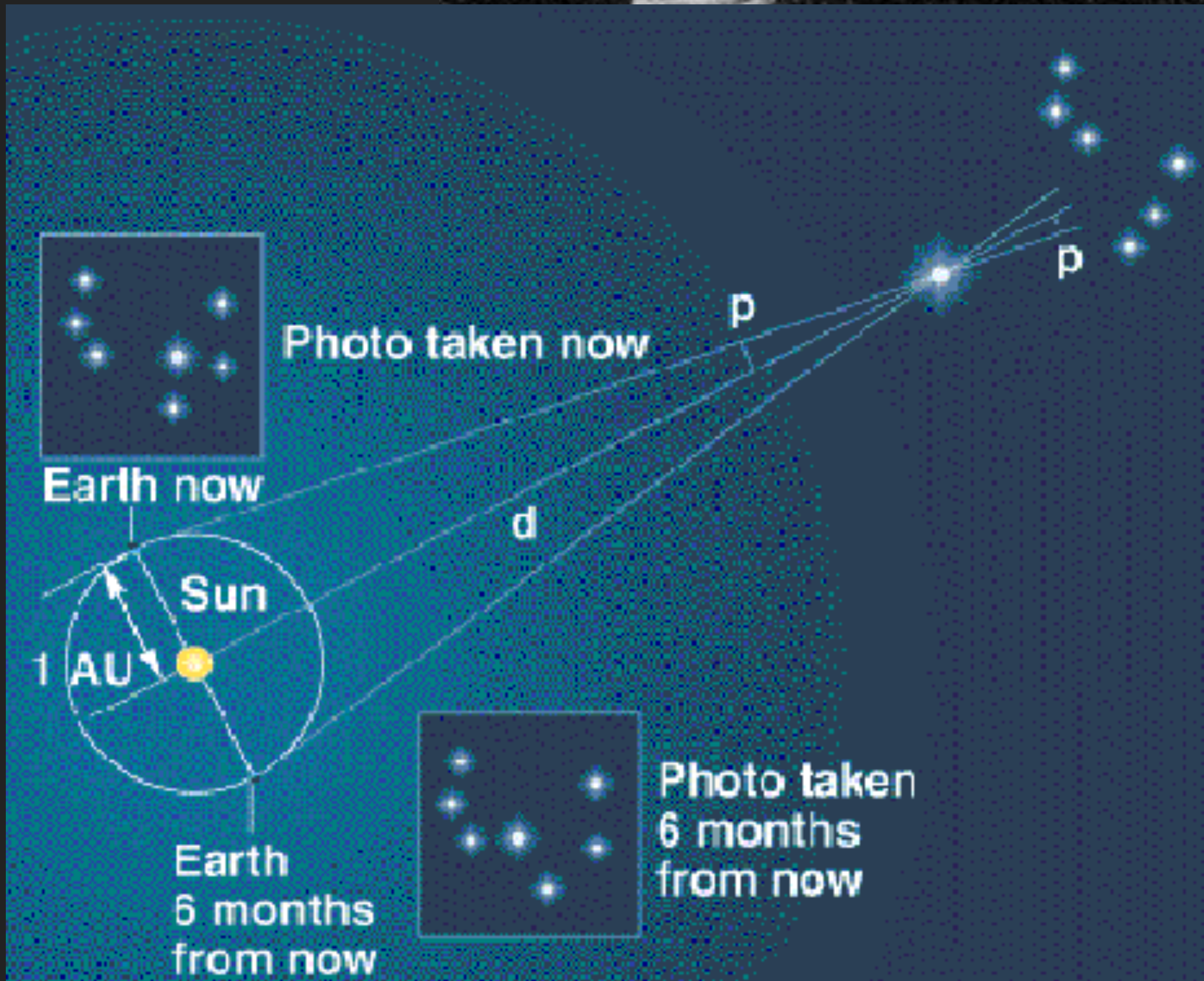
1644-1710

- Can invert this method to measure distances to other planets.
- Now, most accurate distance measurements in the Solar system use radar
- But early measurement of finite speed of light led to Maxwell's equation and Einsteins theory of special relativity

RUNG 6 – NEARBY STARS

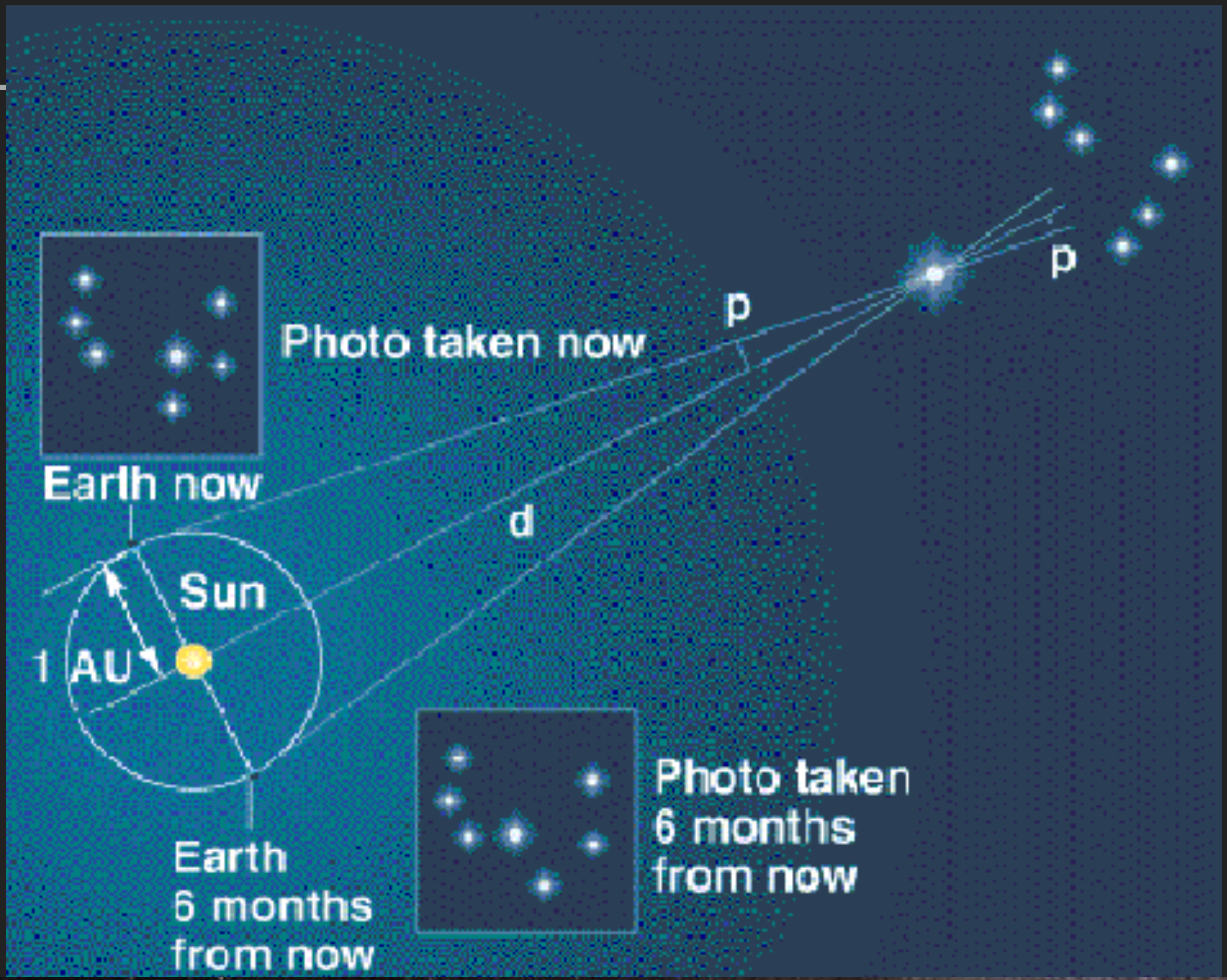
FRIEDRICH BESSEL 1784-1846

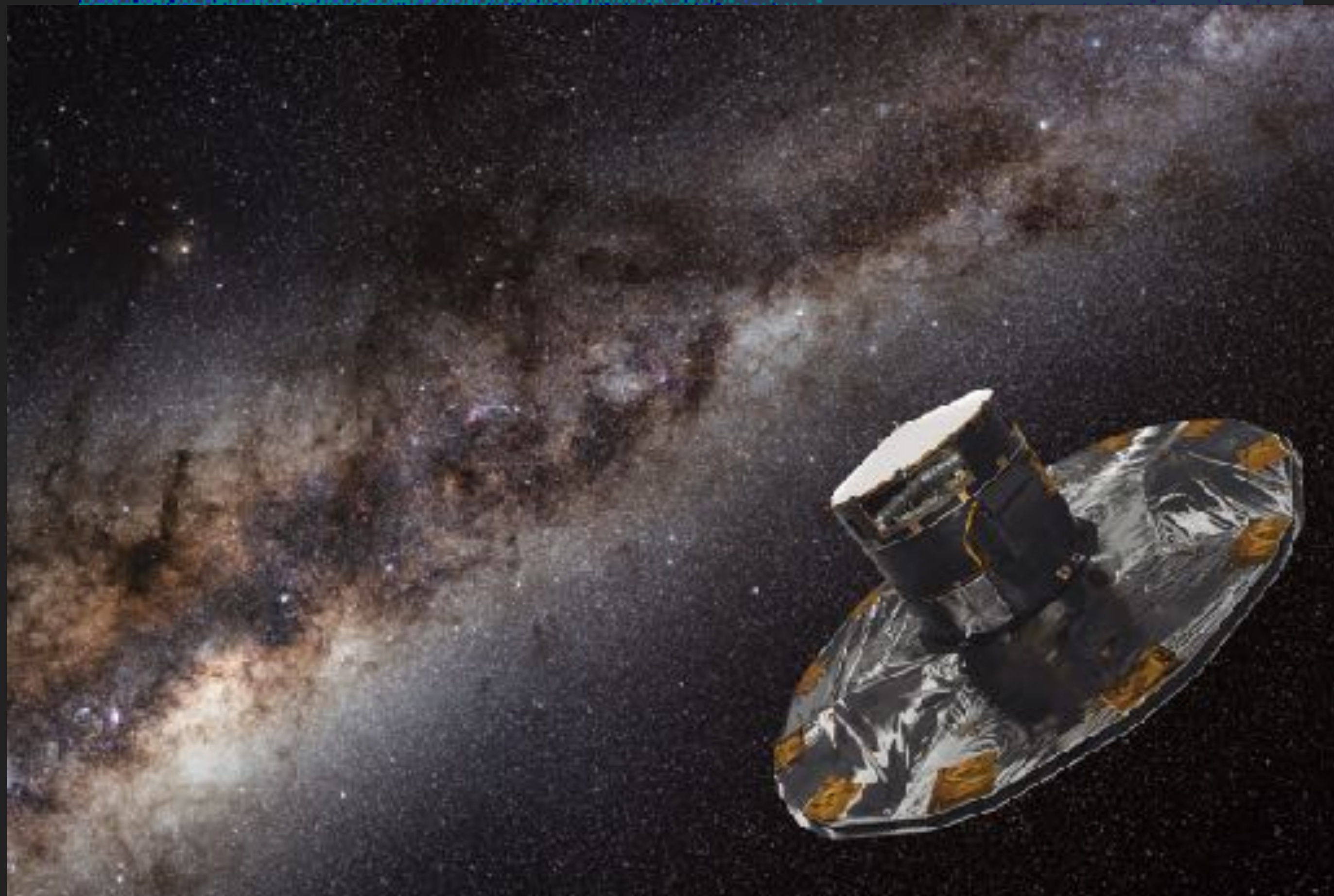
- Parallax method
- Take two observations of a star 6 months apart
- Compare location to stars much further away.
- Simple trigonometry gives distance



FRIEDRICH BESSEL 1784-1846

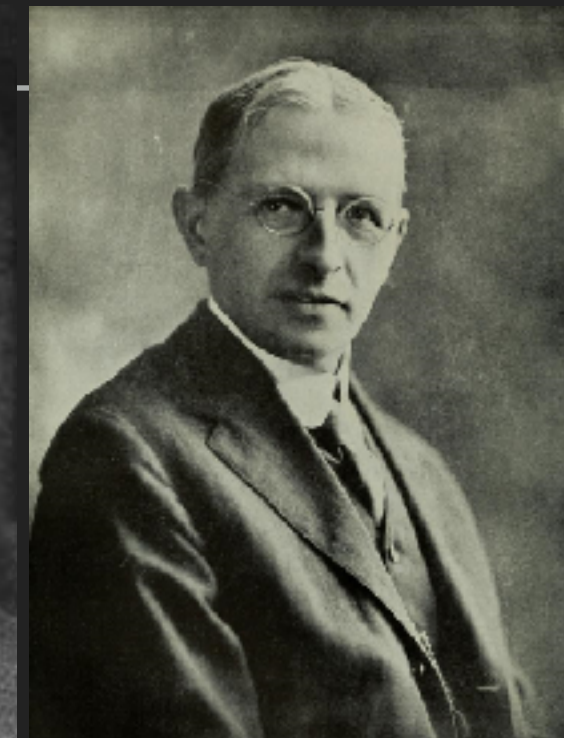
- Requires fairly accurate instrument.
- Ironically, ancient Greeks dismissed Aristarchus's heliocentric model, because it implied a parallax of the stars which was not observed.
- GAIA is currently using parallax to map out much of the Milky Way



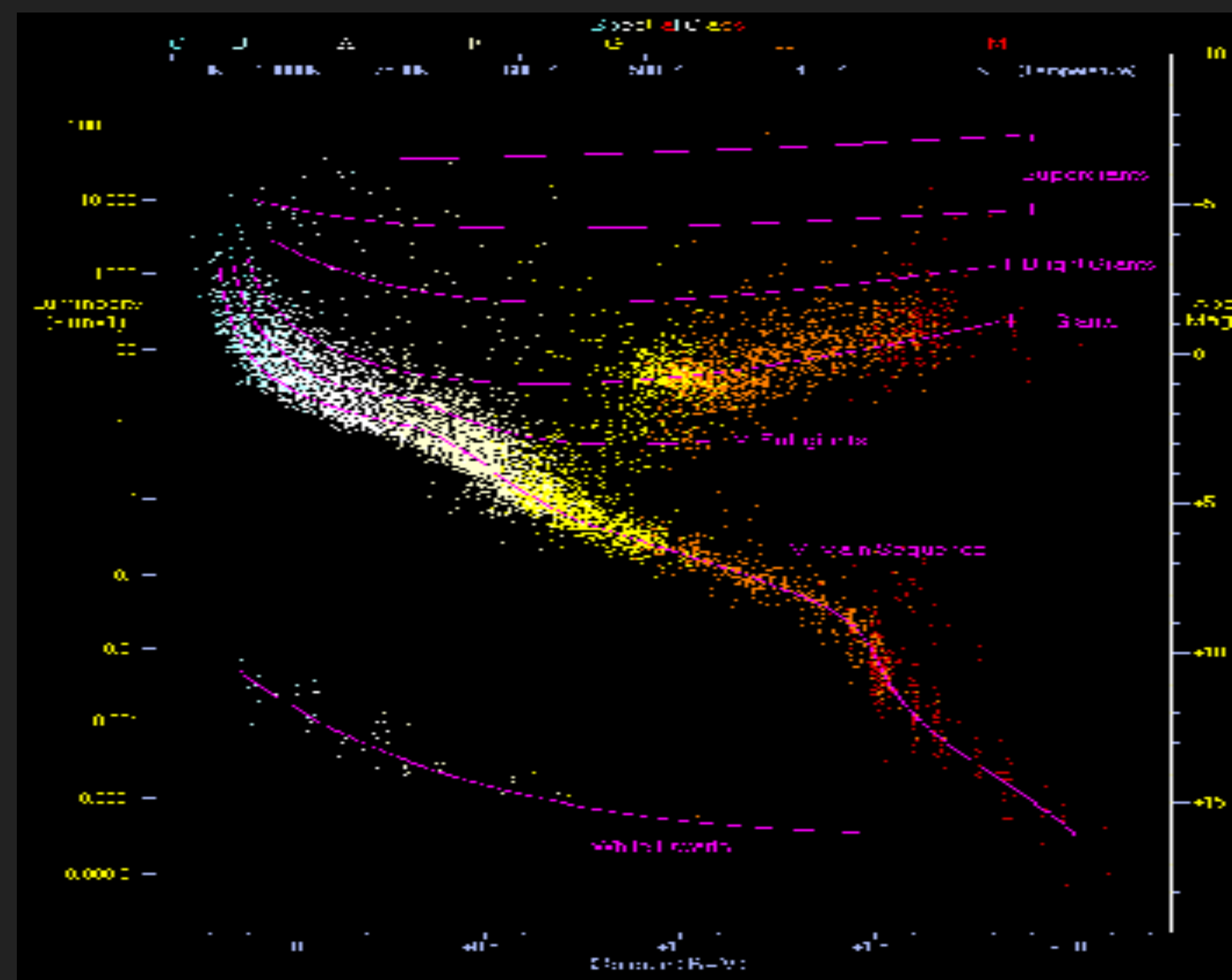


RUNG 7 – MODERATELY DISTANT STARS

EJNAR HERTZSPRUNG 1873-1967
HENRY RUSSELL 1877-1957



- Measure apparent brightness and colour of stars
- Colour of stars is related to absolute magnitude
- Can determine distances up to 300,000 light years.

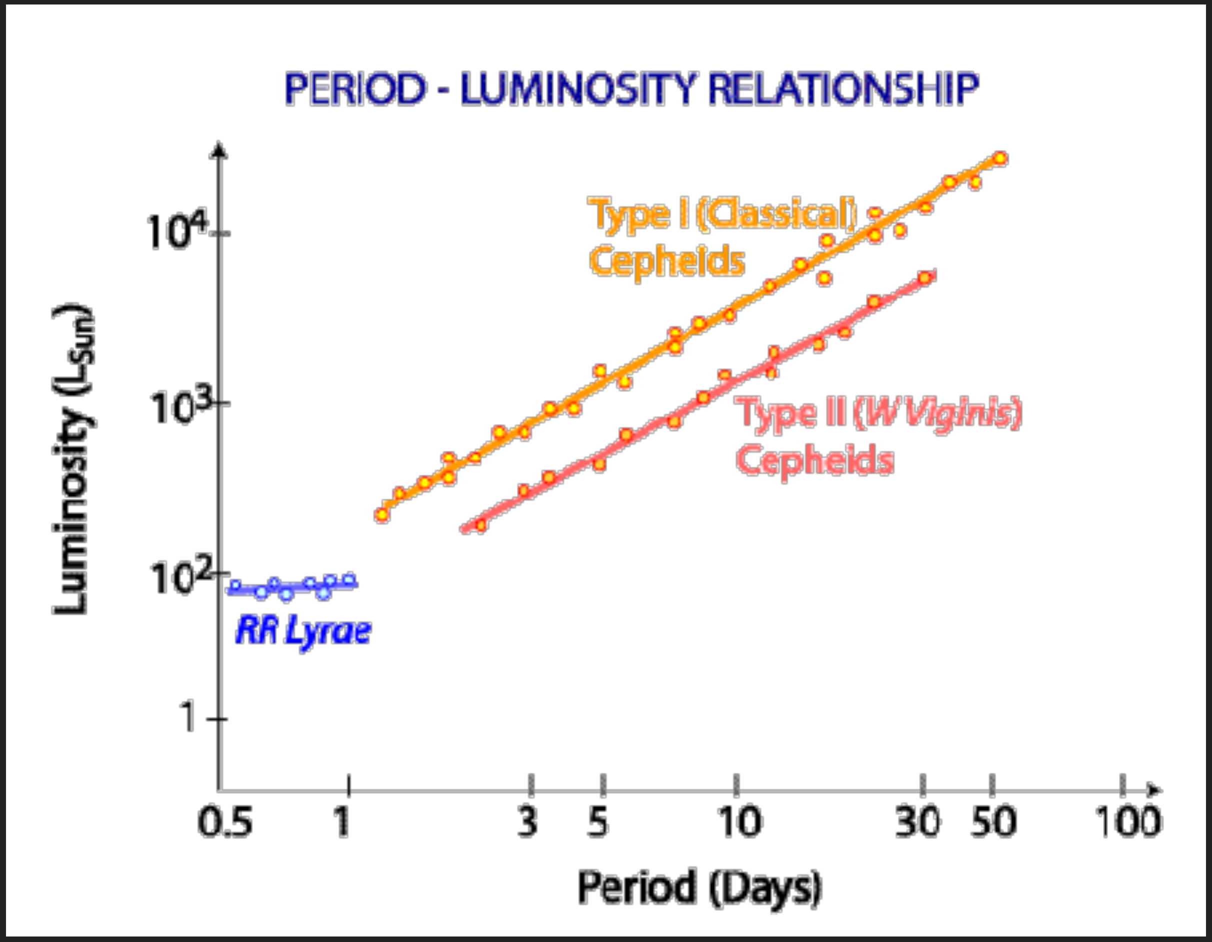


RUNG 8 – VERY DISTANT STARS

HENRIETTA SWAN LEAVITT

1868-1921

- Certain class of stars, *Cepheids*, oscillate in brightness
- Absolute brightness is correlated with period
- Cepheids are very bright. Allow for measurements up to 13,000,000 light years
- Can now measure distances to other galaxies

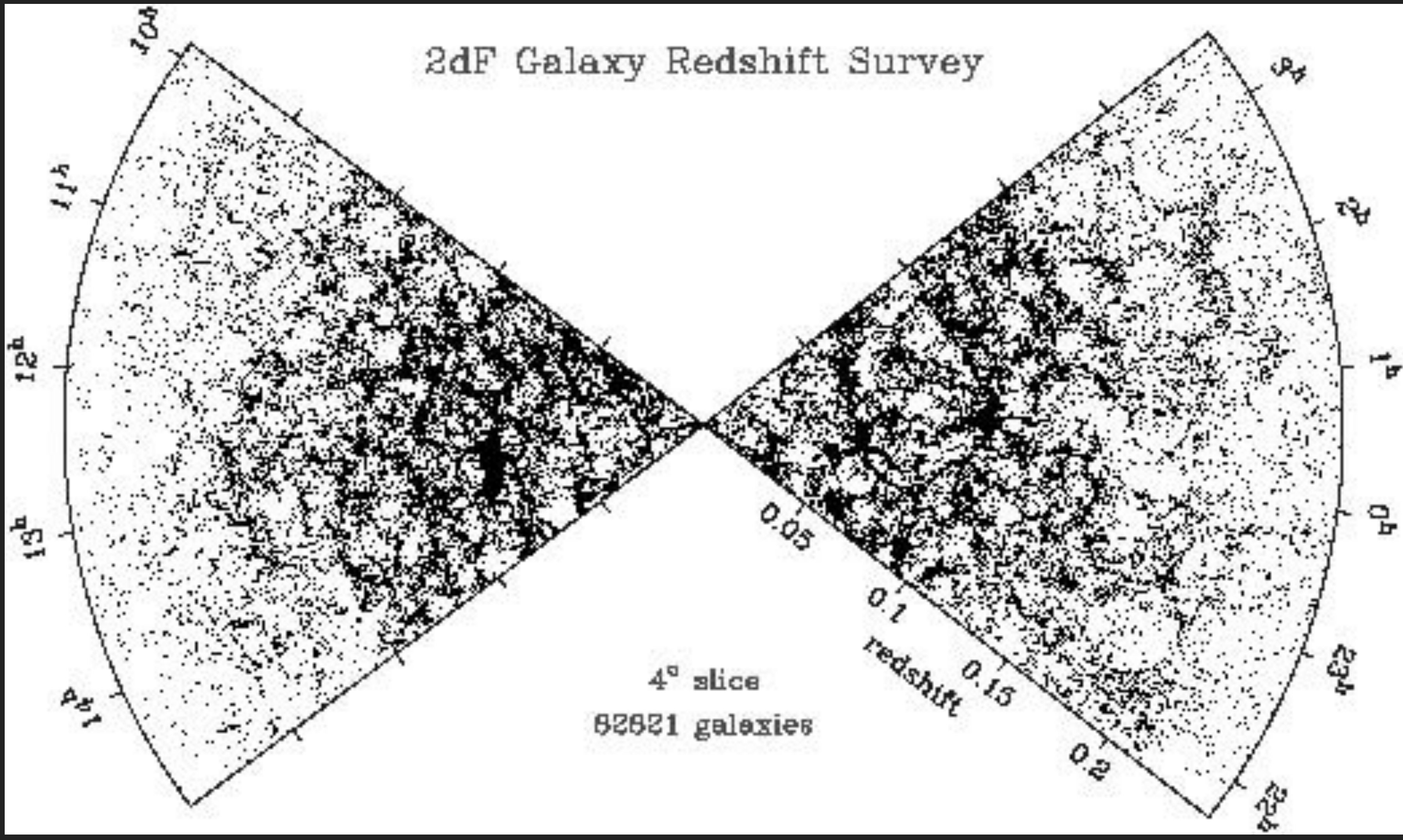


RUNG 9 – THE UNIVERSE

EDWIN HUBBLE

1889-1953

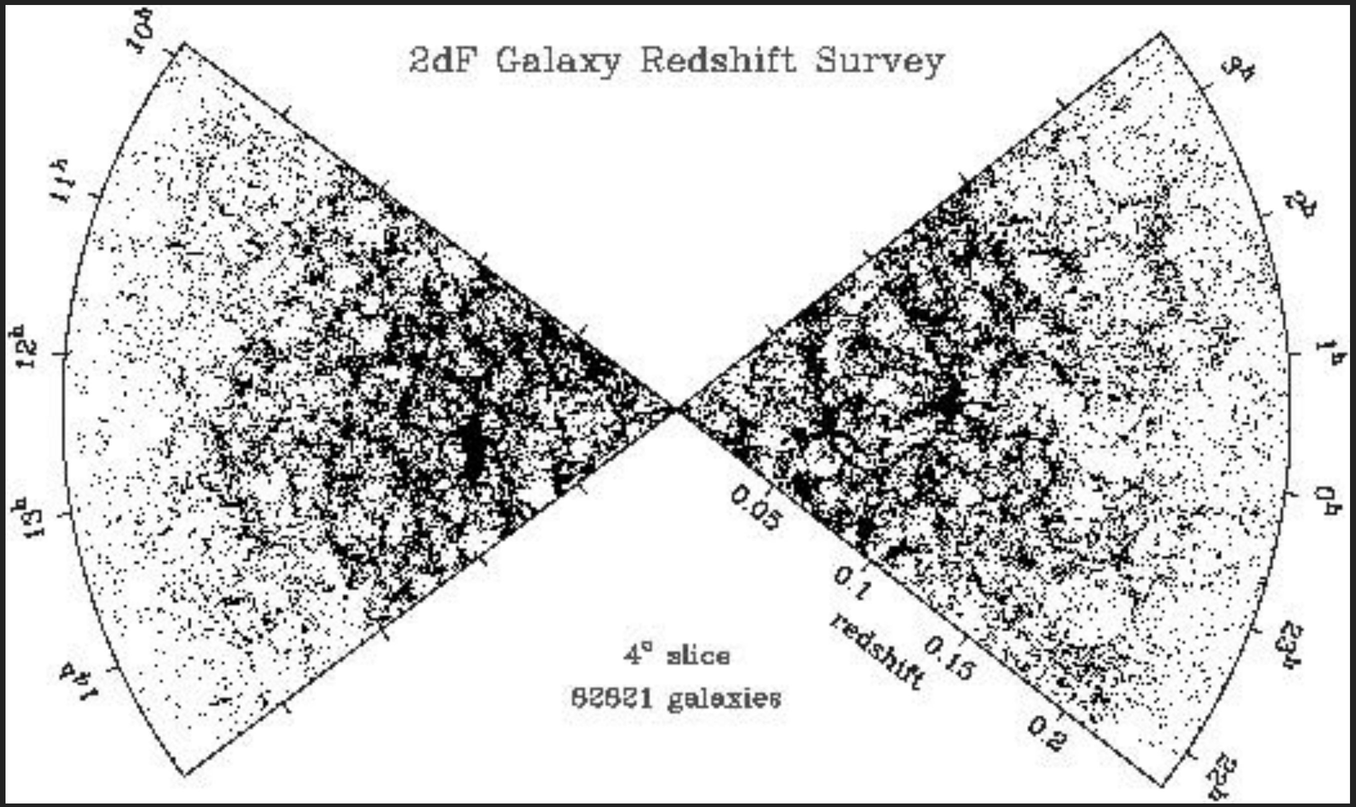
- Notice a correlation between an object's distance and its redshift
- Leads to accurate maps of very large distances

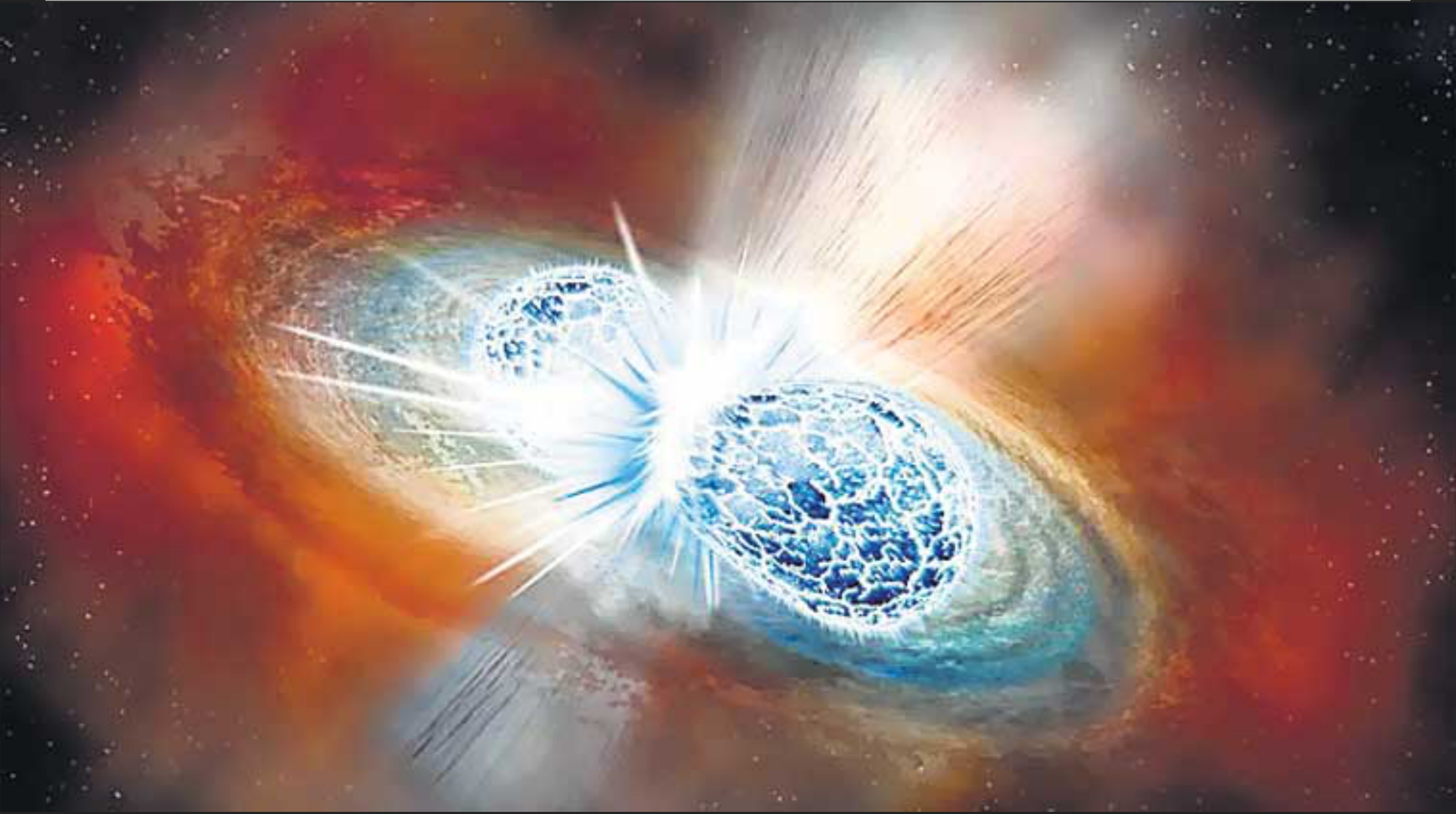


RUNG 1


ORBIS PTOLEMAEI

RUNG 9


2dF Galaxy Redshift Survey
4° slice
62621 galaxies
redshift
0.05
0.1
0.15
0.2
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h



MULTI-MESSENGER ASTRONOMY

A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE 1M2H COLLABORATION,
THE DARK ENERGY CAMERA GW-EM COLLABORATION AND THE DES COLLABORATION,
THE DLT40 COLLABORATION, THE LAS CUMBRES OBSERVATORY COLLABORATION,
THE VINROUGE COLLABORATION, THE MASTER COLLABORATION, et al.

ABSTRACT

The detection of GW170817 (Abbott et al. 2017a) in both gravitational waves and electromagnetic waves heralds the age of gravitational-wave multi-messenger astronomy. On 17 August 2017 the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) (LIGO Scientific Collaboration et al. 2015) and Virgo (Acernese et al. 2015) detectors observed GW170817, a strong signal from the merger of a binary neutron-star system. Less than 2 seconds after the merger, a gamma-ray burst (GRB 170817A) was detected within a region of the sky consistent with the LIGO-Virgo-derived location of the gravitational-wave source (Abbott et al. 2017b; Goldstein et al. 2017; Savchenko et al. 2017). This sky region was subsequently observed by optical astronomy facilities (Abbott et al. 2017c), resulting in the identification of an optical transient signal within ~ 10 arcsec of the galaxy NGC 4993 (Coulter et al. 2017; Soares-Santos et al. 2017; Valenti et al. 2017; Arcavi et al. 2017; Tanvir et al. 2017; Lipunov et al. 2017). These multi-messenger observations allow us to use GW170817 as a standard siren (Schutz 1986; Holz & Hughes 2005; Dalal et al. 2006; Nissanke et al. 2010, 2013), the gravitational-wave analog of an astronomical standard candle, to measure the Hubble constant. This quantity, which represents the local expansion rate of the Universe, sets the overall scale of the Universe and is of fundamental importance to cosmology. Our measurement combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using electromagnetic data. This approach does not require any form of cosmic "distance ladder" (Freedman et al. 2001); the gravitational-wave (GW) analysis can be ... the luminosity distance out to cosmological scales directly, without the use of intermedi- ... Hubble constant to be $70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}

ASTC02 - COSMIC DISTANCE LADDER

observed by optical astronomy facilities (Abbott et al. 2017c), resulting in the identification of an optical transient signal within ~ 10 arcsec of the galaxy NGC 4993 (Coulter et al. 2017; Soares-Santos et al. 2017; Valenti et al. 2017; Arcavi et al. 2017; Tanvir et al. 2017; Lipunov et al. 2017). These multi-messenger observations allow us to use GW170817 as a standard siren (Schutz 1986; Holz & Hughes 2005; Dalal et al. 2006; Nissanke et al. 2010, 2013), the gravitational-wave analog of an astronomical standard candle, to measure the Hubble constant. This quantity, which represents the local expansion rate of the Universe, sets the overall scale of the Universe and is of fundamental importance to cosmology. Our measurement combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using electromagnetic data. This approach does not require any form of cosmic "distance ladder" (Freedman et al. 2001); the gravitational-wave (GW) analysis can be used to estimate the luminosity distance out to cosmological scales directly, without the use of intermediate astronomical distance measurements. We determine the Hubble constant to be $70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (maximum a posteriori and 68% credible interval). This is consistent with existing measurements (Planck Collaboration et al. 2016; Riess et al. 2016), while being completely independent of them. Additional standard-siren measurements from future gravitational-wave sources will provide precision constraints of this important cosmological parameter.