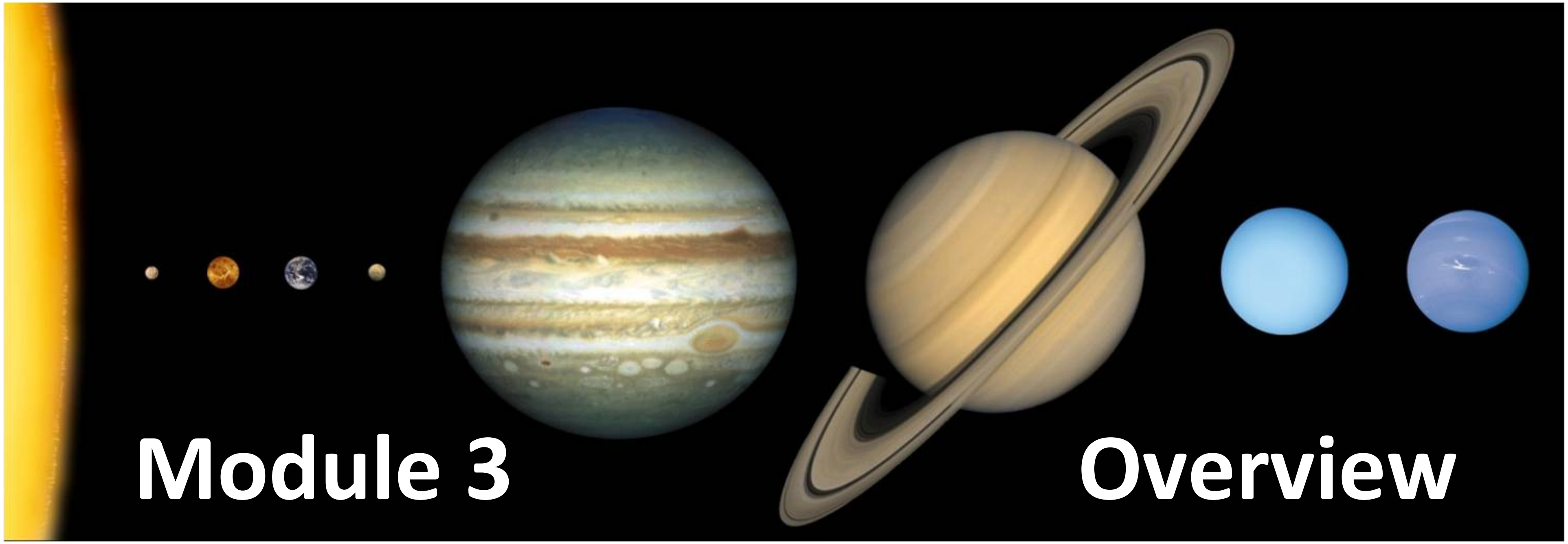
Earth Sciences 2150 – Fall 2023
Solar System and Planetary Science



Module 3: An Introduction to Historical and Modern Observations of the Solar System, and the Context of the Solar System in the Galaxy and Universe

EASC 2150: The Solar System
The Plan for Today

Our understanding of the heavens, and our place in the unimaginable Universe

• The long human interest in the heavens (often for the wrong reasons) and what we have learned – and where the terminology we use comes from.

• The ways in which we are NOW able to gain information about the Solar System and try to understand it.

• The Universe, galaxies, stars, cosmological time and other mind-expanding things – prepare to feel insignificant!

• A few general facts about the Solar System – to build your framework of terms and concepts.

Human Observation of the Solar System and Heavens

- Looking at the skies is an ancient human activity; likely even older than agriculture (but linked to it).

- Our ancestors had limited ability to see things and measure time.

- The Sun is visible because of the light it emits. Other objects in our solar system are visible because they reflect sunlight. Stars shine and twinkle. The skies were clear and nights were dark and long.
So early Humans wondered…

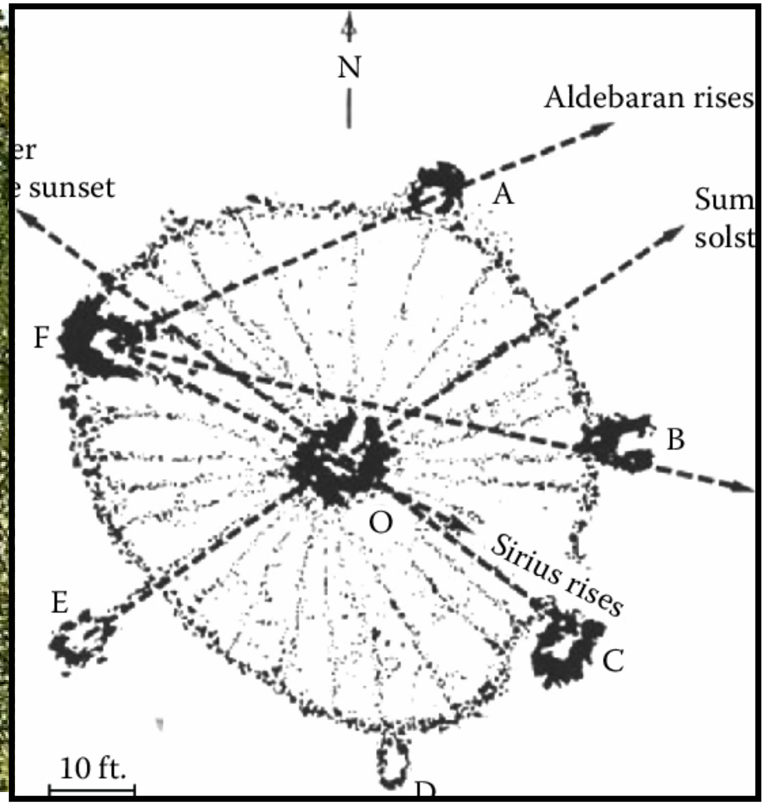
• The oldest known ***written records*** of astronomical observation come from the Sumerian civilization (~3,000 BCE) in the Middle East. Sumeria became part of the Babylonian Empire, which continued observations. But these were not the start. Why were humans interested in stargazing? Was it purely mystical or partly practical?

• Stone circles with supposed astronomical significance are found in many places in the world. Stonehenge dates from **~3,000 BCE** but other similar structures were built elsewhere in Europe thousands of years earlier. If they were not made of stone, they wouldn't survive.

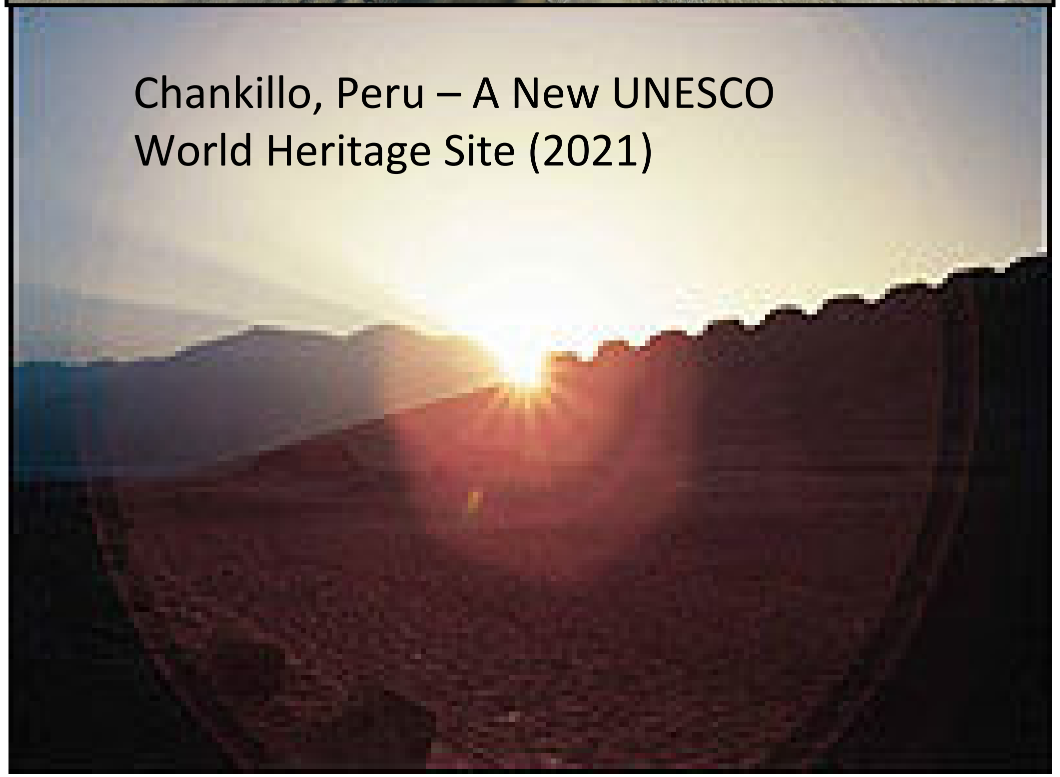
How it works

• Stonehenge appears to be some kind of calendar - it was built to track seasons for practical and mystical purposes.

• At each summer solstice, spring equinox etc. the sun rises through the opening in a different standing stone. Modern British Druids still gather at Stonehenge on June 21st, but access is restricted.



• Medicine Wheels are possibly equivalent structures built by the plains Indians of western North America using small stones. This one, the Bighorn Medicine Wheel in Montana, is only a **few hundred years old**. The oldest wheel known, which is in Majorville, Alberta, dates from the same period as Stonehenge (i.e. **~3,000 BCE**). They are aligned with astronomical parameters, but the exact details are unclear. They have not survived as well as structures like Stonehenge.



Chankillo, Peru – A New UNESCO World Heritage Site (2021)

- The oldest astronomical observatory known in the Americas is in Peru, on a mountain ridge; ~ 400 BC.

- Like the structures at Stonehenge, those at the site near Lima, Peru, align with the directions of sunrise and sunset at summer and winter solstices. But they are now slightly inaccurate. Why is this?
- **Because the Heavens are NOT constant, even if they seem so to us!**

Practical versus Theoretical Astronomy

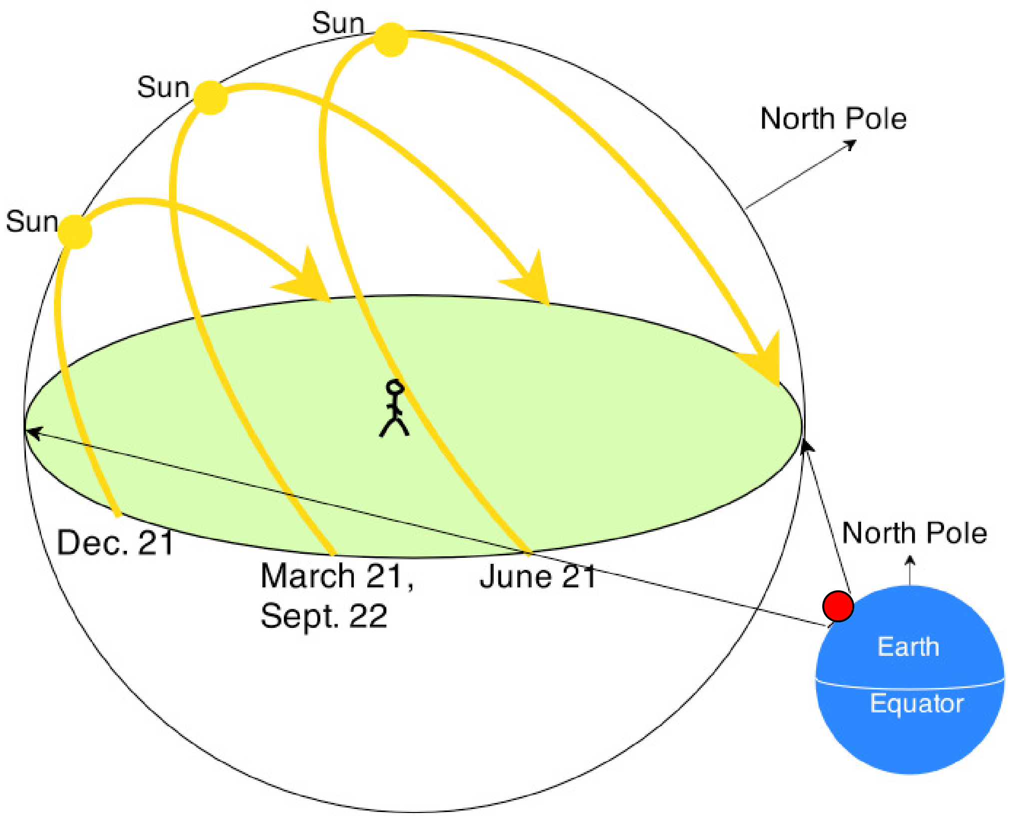
- In the Babylonian Empire and in the ancient world, an accurate calendar was essential for business and administration by early cultures and vital for agriculture.
- Astronomy had a **purely practical aspect** to the Babylonians. There is no evidence that they were interested in gaining a scientific understanding of all this. But they wanted to know when to plant crops and when taxes should be collected.

- Stone Circles, Medicine Wheels and comparable structures all appear to have been designed to act as calendars rather than to understand motions of the heavenly bodies. They had to be 'calibrated' by observations over many years.
- **Nevertheless, repeated observations made from early structures indicated COMPLEXITY. Why does the length of days vary? Why is the Sun 'higher' in the summer skies?**

Our distant ancestors could observe….

- The daily motion of the sun through the sky.
- The changes in sunrise, sunset, day length and the position of the sun in the sky with the passing of the seasons.
- The path of the Moon through the sky and the **phases of the Moon**, which define the concept of months (NOTE: Lunar Months are not the same as Calendar Months).
- The stars, and their patterns – which appear fixed, even though the stars move with night, day and the seasons.
- **Some peculiar stars that appear to 'wander' through the stars in an unusual but repeated pattern.**
- **Interesting but scary events like solar and lunar eclipses. The loss of the Sun (even briefly) had great import…..**

The Sun's Path



An observer in the northern hemisphere (at the red dot) sees the Sun travel on paths through the sky that vary, depending on latitude. These define summer and winter solstices, and the spring and fall (autumn) equinoxes.

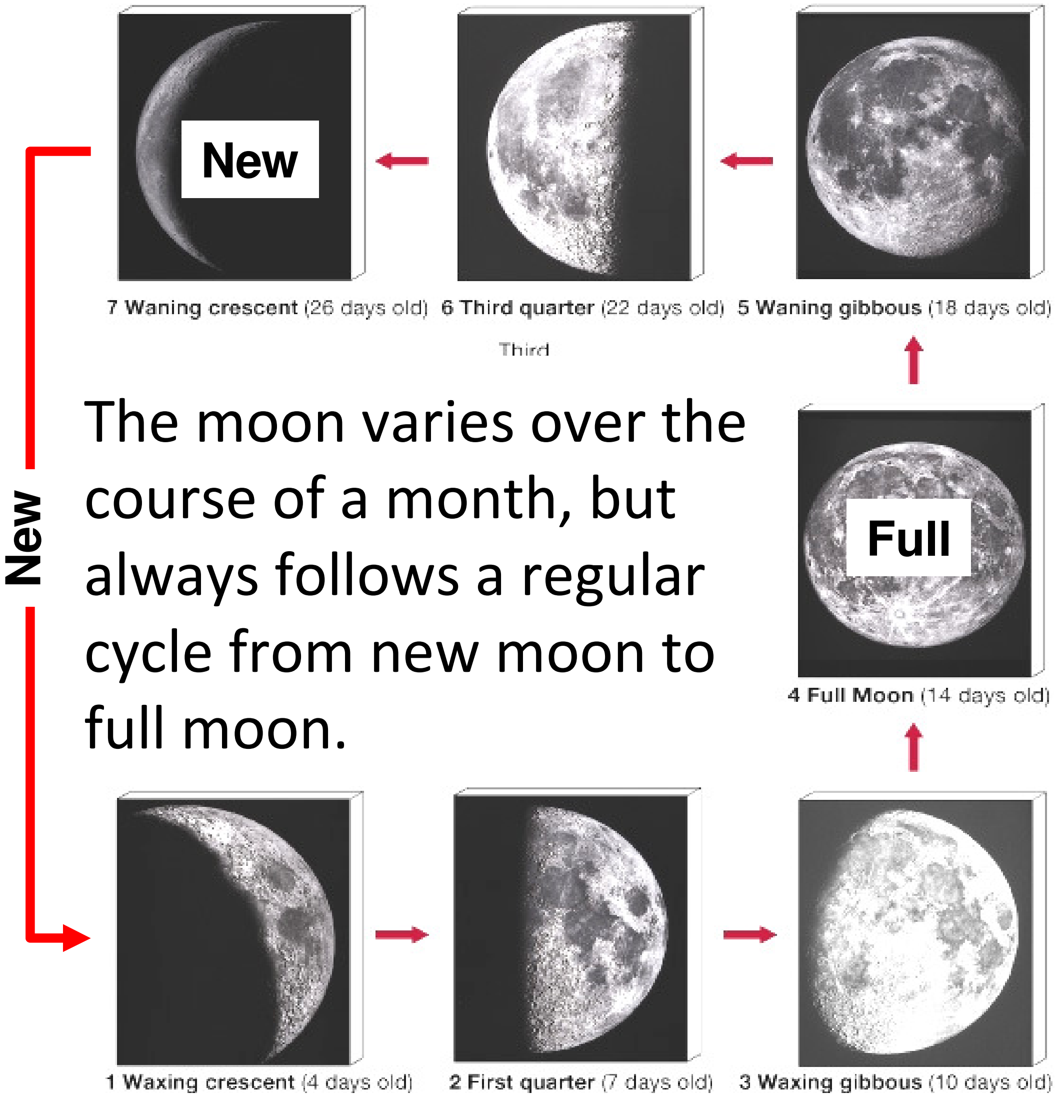
- The Sun follows a daily path through the sky, appearing over the horizon approximately in the east and disappearing below the horizon approximately in the west.
- The Sun's daily path through the sky changes over the course of a year, being highest above the horizon in summer and lowest in winter.
- The length of the day changes with the seasons and is only rarely the same length as the night. This is where the word "Equinox" comes from.

Understanding the Solar Calendar

- The quest to understand the seasons and develop a calendar is probably one of the first aspects of astronomy.
- The winter solstice is a time of celebration (Christmas) as it means that spring **will** come again. It predates Christianity.
- The Spring equinox (vernal) is a time to start planting crops in the northern hemisphere; the Fall equinox (autumnal) marks the beginning of harvest time.
- We see these patterns as **permanent**, but over time there is a wobble in Earth's rotation axis – it 'precesses'. The seasons will shift in deep time. Our calendar addresses this 'problem' by the use of leap years, to keep us in sync!
- The Solar Calendar was the rhythm of ancient existence.

Phases of the Moon

Waning Phases



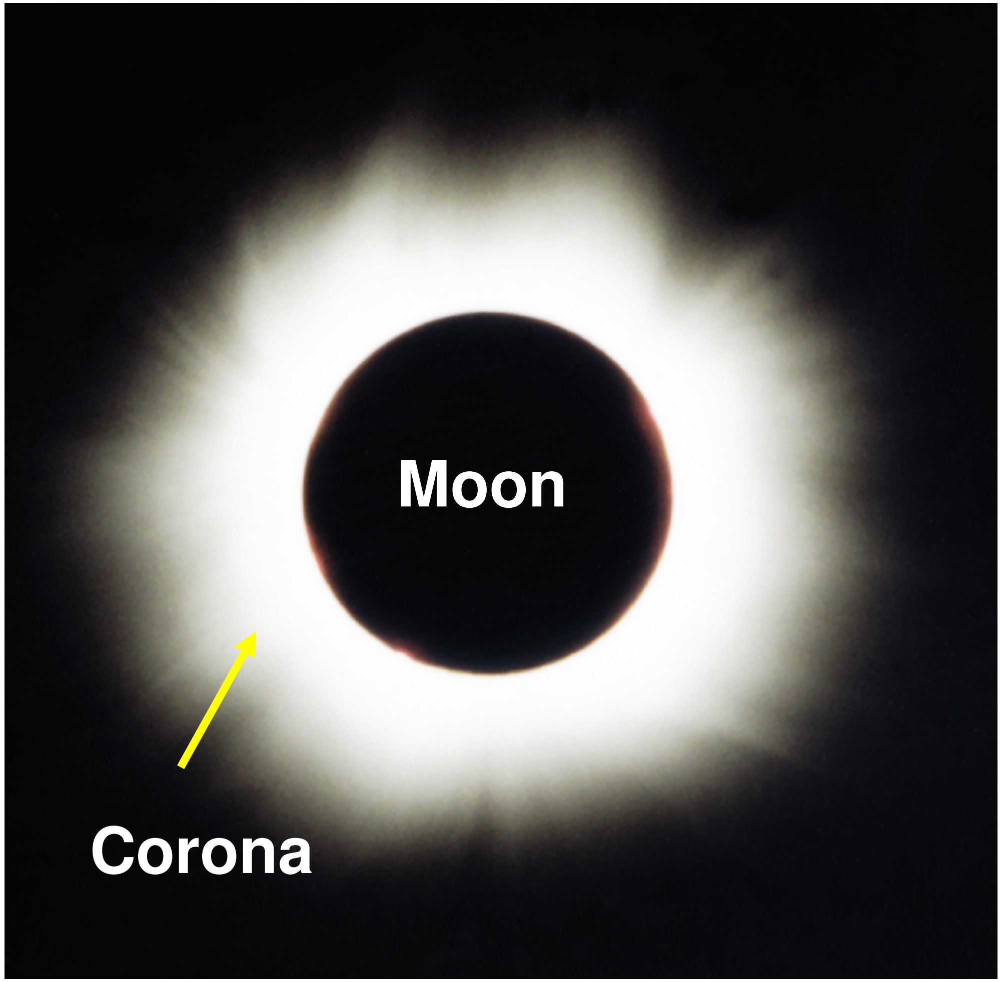
The moon varies over the course of a month, but always follows a regular cycle from new moon to full moon.

Waxing Phases

- Like the Sun, the Moon follows an E-to-W path through the sky on a daily basis and is higher or lower in the sky with the seasons.
- A full moon appears on the eastern horizon at dusk.
- There is a 28-day cycle to these patterns. The phases also link to tidal cycles for coastal peoples and affect the behaviour of animals.
- The Sun was usually a God to the ancients, but the Moon was usually a Goddess.

Solar Eclipses – Total and Partial

- Occasionally there is a partial or total **eclipse of the Sun**. It is always at a New Moon.
- **But there isn't a solar eclipse *every* time there is a new moon, and they are seen only in certain places.**
- **Eclipses were seen as malevolent things – they were very scary for early peoples.**
- Much effort went into the prediction of eclipses in early days.



Total solar eclipse – here we see the vast solar corona (atmosphere), which is normally invisible to us.

Lunar Eclipses – only at Full Moons, but not every time

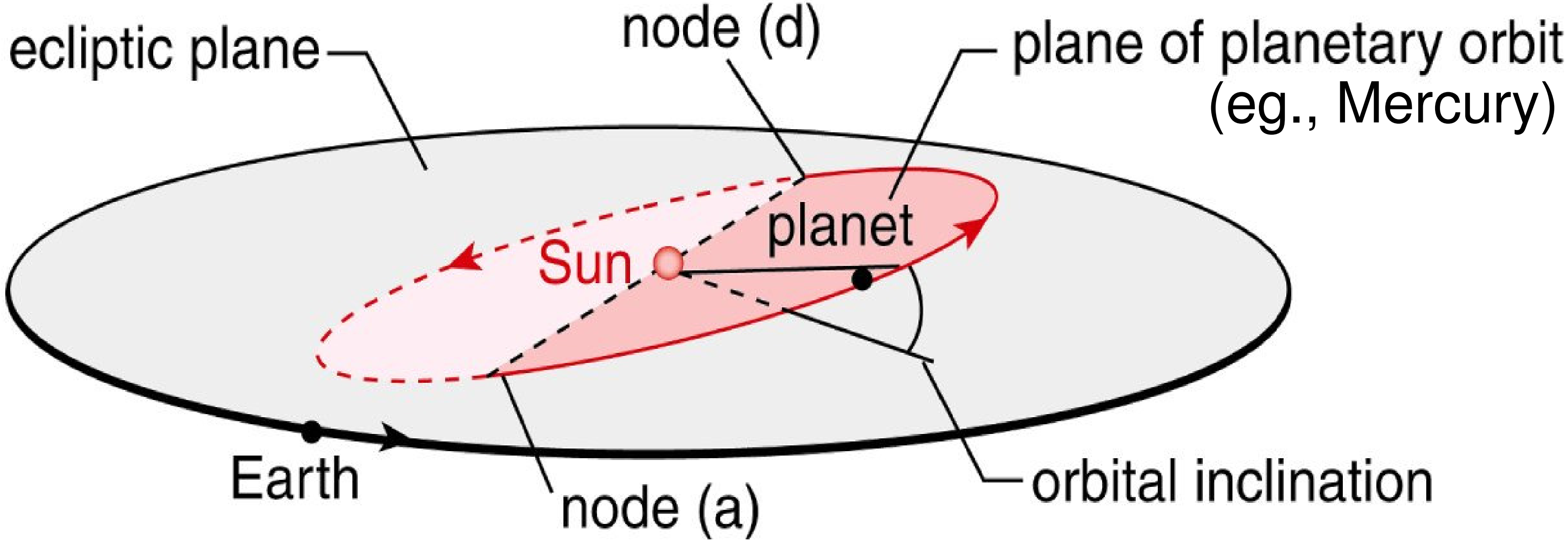
- There was a blood moon eclipse on May 26, 2021. I think it was cloudy in St. John’s.

- These are seen with some eclipses, and form when the light from the Sun has to pass through Earth’s atmosphere to reach the Moon. Loss of shorter wave lengths accentuates red and orange colours.

Causes of Solar Variations and Eclipses

- We now understand these effects well, but there were many steps in reaching this point – challenges were related to the prevailing concept that WE are the centre of the Universe, which of course is not true.
- The Sun rises and sets because of Earth's **rotation**; the variations through the year are due to **inclination** of the Earth's rotation axis, which changes the apparent path.
- The phases of the Moon record changes in the degree of lunar illumination from our viewpoint, as the Moon orbits around us. **The dark side of the Moon is NOT always dark!**
- Eclipses are a complex function of orbital geometry in the Earth-Moon system. This is a more complex topic……
- **All these result from orbital motions in the Solar System.**

Ecliptic Plane – contains Earth's orbit and the Sun



• The search for eclipses showed that they always occurred in the same plane in the sky – which could be measured.

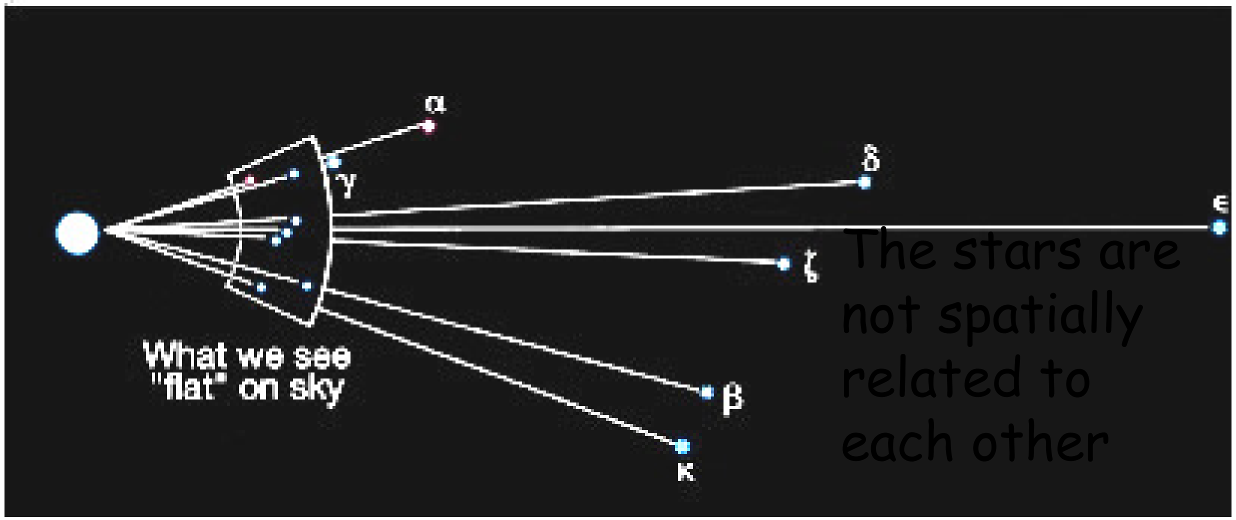
• The **Ecliptic Plane** is defined because ***eclipses can only occur in this plane – only here can the moon come between us and the sun.*** The same plane was also where the 'wandering stars' (planets) moved through the sky (more or less). As shown, the Moon is NOT in the Ecliptic Plane most of the time…….

The Stars – Rather Different Behaviour

- The stars pass across the night sky from E to W on a daily basis just as do the Sun and Moon.
- The patterns of stars (called **the constellations**) appear to be **fixed** as they move across the sky.
- But unlike the Sun and Moon, some constellations are visible from a particular location on Earth *only* during certain seasons. Some are only visible from one hemisphere – e.g., the Southern Cross.
- However, the constellations always **return** to their same locations at the same time from one year to another. So they are **very** predictable.
- Some very useful stars (e.g. Polaris) are fixed, at least with reference to *our* history. We navigate by them. But, again – things change over time…due to that problematic wobble in Earth’s rotation axis.

Pattern of stars in the constellation Orion

Fanciful interpretation of the pattern



- The sky is divided into 88 **constellations**.

The Constellations are groupings of stars that form what we humans interpret as patterns.

The individual stars of any constellation are at very different distances from Earth. Their patterns would look quite different if viewed from another location in the galaxy.

But they are useful!

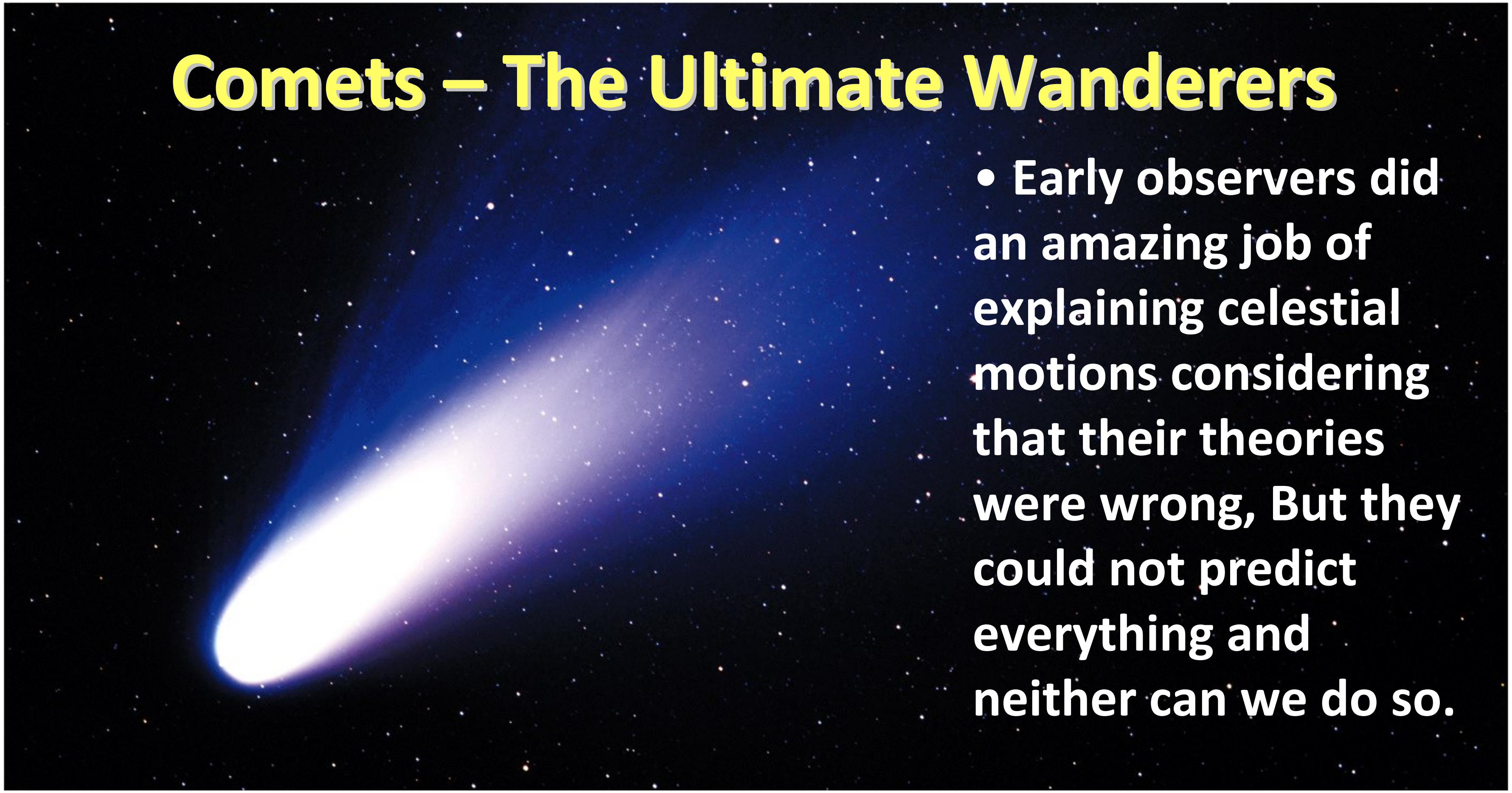
The Planets – The Wandering Stars

- Planets are different. *Over the course of one night*, planets move from E to W along with the stars.
- *Over the course of many nights*, a planet doesn't stay fixed relative to the stars but (*usually*) appears to travel slowly from **W to E through the fixed patterns of stars**. But planets will sometimes seem to move in the other direction (E to W) for a while. This **Retrograde Motion** caused many problems.
- All planets move (more or less) along the **Ecliptic Plane**.
- This motion relative to the pattern of the stars is the origin of the word **planets**, which comes from the ancient Greek word for "travelers" or "wanderers".
- Five planets were known to the ancient astronomers: **Mercury, Venus, Mars, Jupiter** and **Saturn**.
- The **Sun** and **Moon** were also considered as **planets** by the ancients although their motions are not the same. The early astronomers had no way to estimate size or distance.

The Zodiac and the Ecliptic

- The Sun, the Moon and the planets all appear to travel across the sky in approximately the same path or ‘plane’, which is known as the **Ecliptic Plane**. Eclipses will always be in this plane.
- As planets travel along the ecliptic they appear to move from W to E against a background of 12 specific constellations known as the **Zodiac**, which have supposed astrological significance.
- These constellations are the ones we are most familiar with, and the ‘signs of the Zodiac’ are the constellations where the Sun would also sit at a given time of the year. However, you can’t see the sun and stars together.
- **For example, I’m a PISCES, born on March 3rd. What sign are you? And does it really make any difference? Astrology is complete nonsense, but it continues to fascinate some.**

Comets – The Ultimate Wanderers



- Early observers did an amazing job of explaining celestial motions considering that their theories were wrong, But they could not predict everything and neither can we do so.

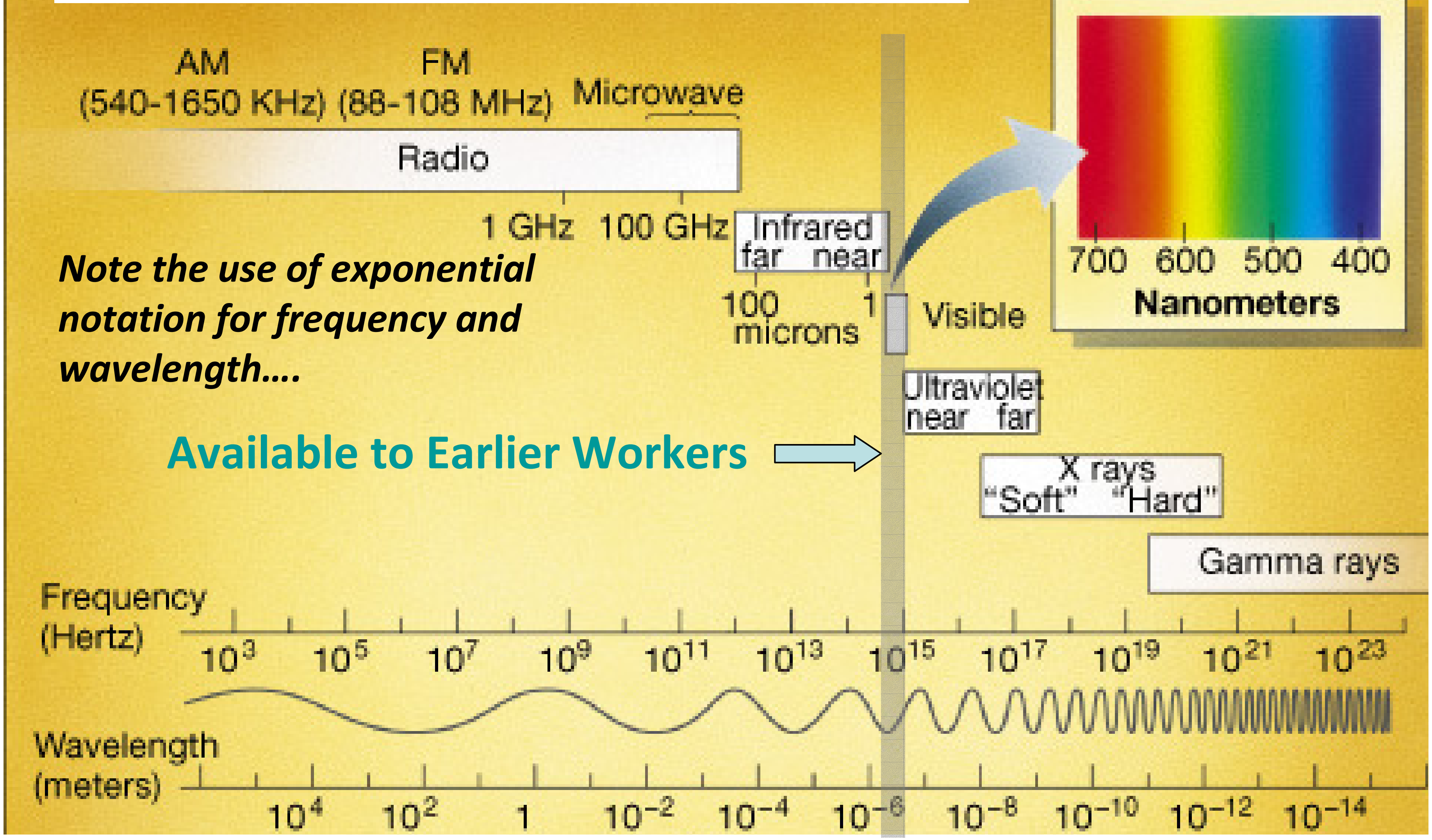
- Other things seemed not to have patterns – like comets, for example. Their appearance and locations were not really predictable, and some would be seen only by one generation of observers. The same applies to **Novae** and **Supernovae** – suddenly bright stars. What are these ?

Modern Methods and Techniques

- The telescope had a huge impact. But early instruments for measurement of angles had an equally vital impact. They enabled actual measurements of where things are.

- We now use orbital telescopes like Hubble. It is just one of many such telescopes. The James Webb telescope is the latest and it will amaze us. We also have new methods for Earth-based observations.

The Importance of Analyzing EM Radiation



For the ancients and until about 150 years ago, we were limited to the visible spectrum. The use of other types of radiation has now given new dimensions to our understanding and observation.

Direct samples of material from elsewhere in the Solar System arrive on Earth as rare meteorites.

(known to the ancients but usually ascribed to Gods)

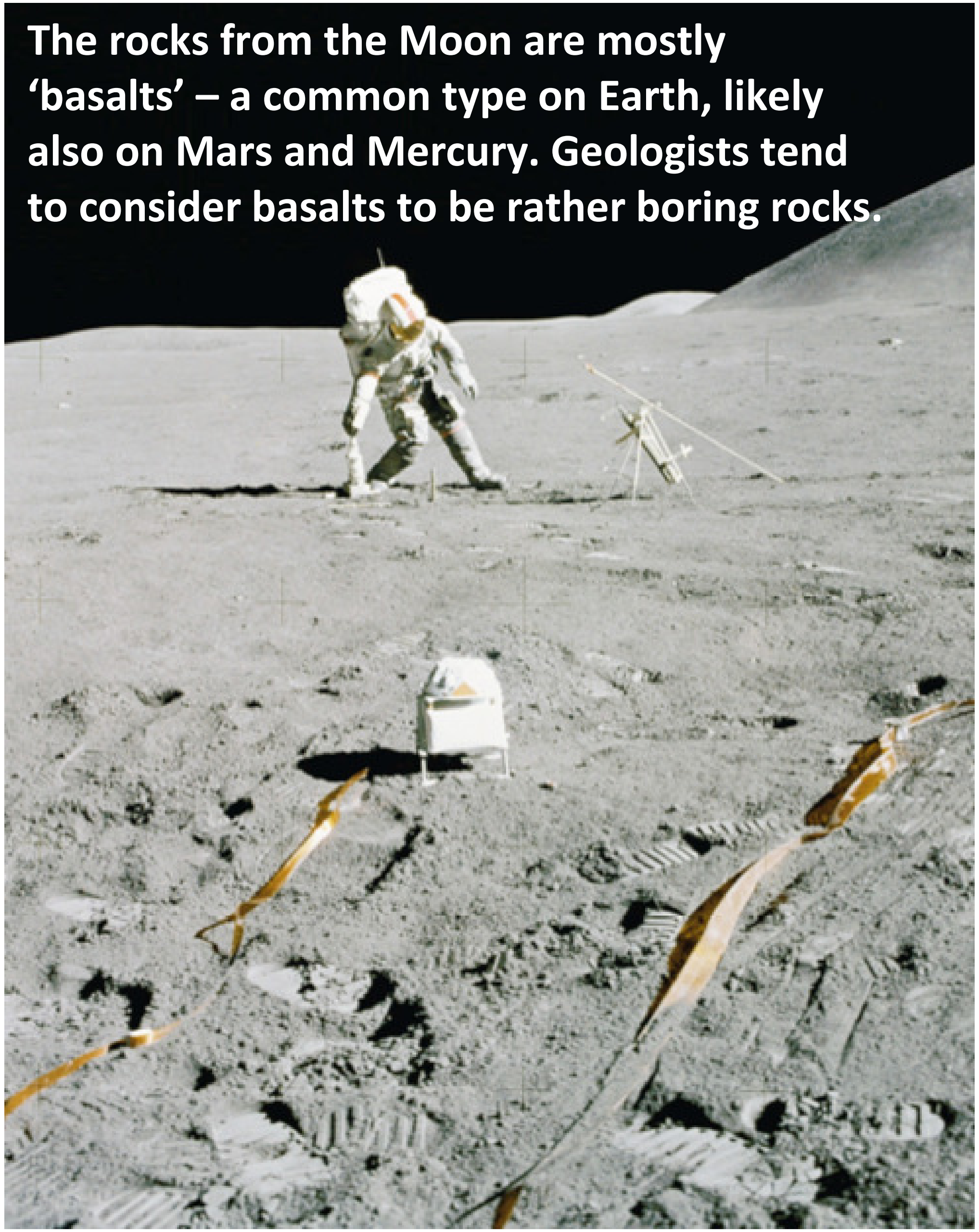
The Barringer crater of Arizona formed ~50,000 years ago as a result of the Canyon Diablo meteorite colliding with Earth.

This is a fragment of the Canyon Diablo meteorite. The whole thing was probably ~100 m in diameter. Most of it was vapourized – no iron ore!

Direct Sampling

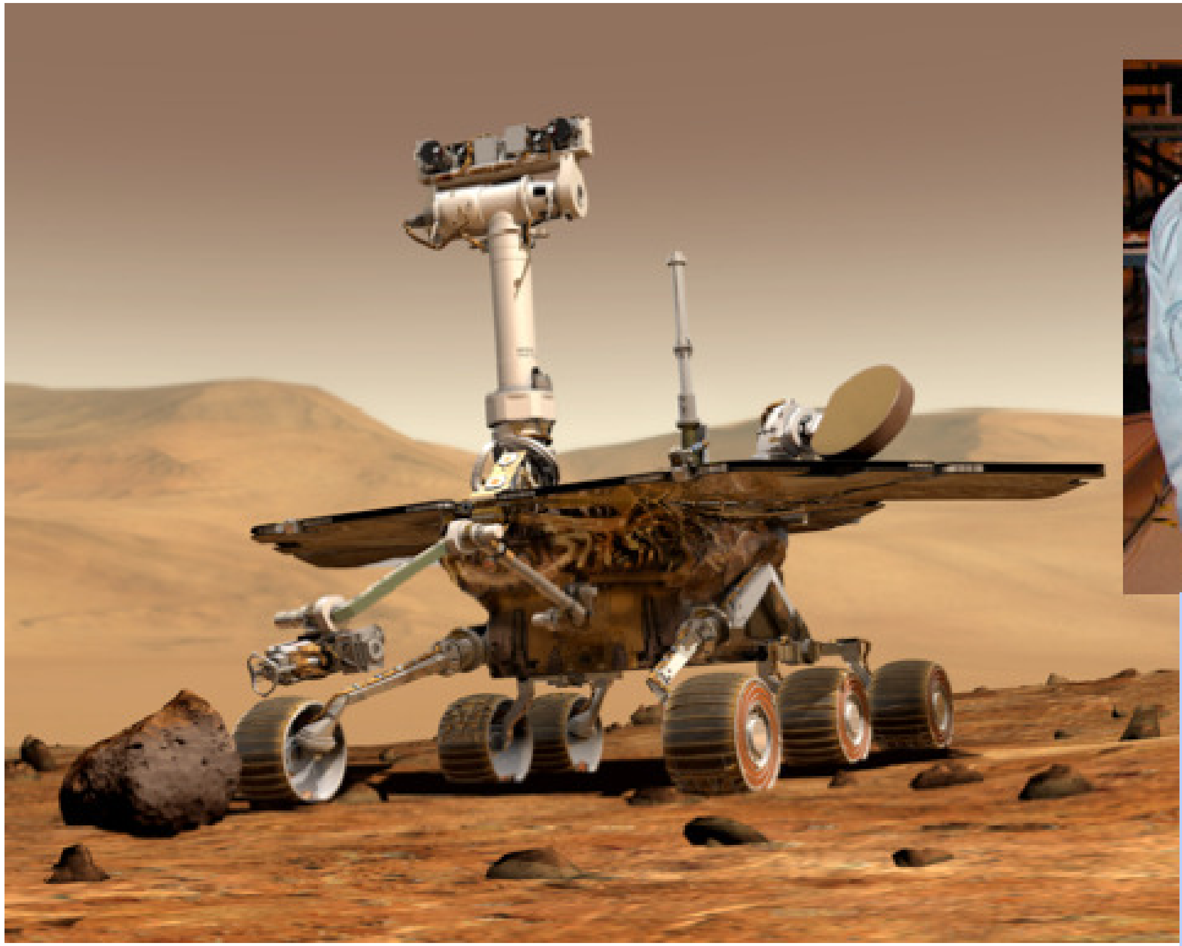
• American astronauts visited the Moon between 1969 and 1972 as part of NASA's Apollo program. They returned to Earth with ~380 kg of rock samples. So we know the composition and age of the surface – or at least some of it. Samples from comets have also been returned to Earth.

• This image shows an astronaut deploying seismic sensors for moonquakes.



Mars Desert Research Station, operated by the Mars Society in Utah.

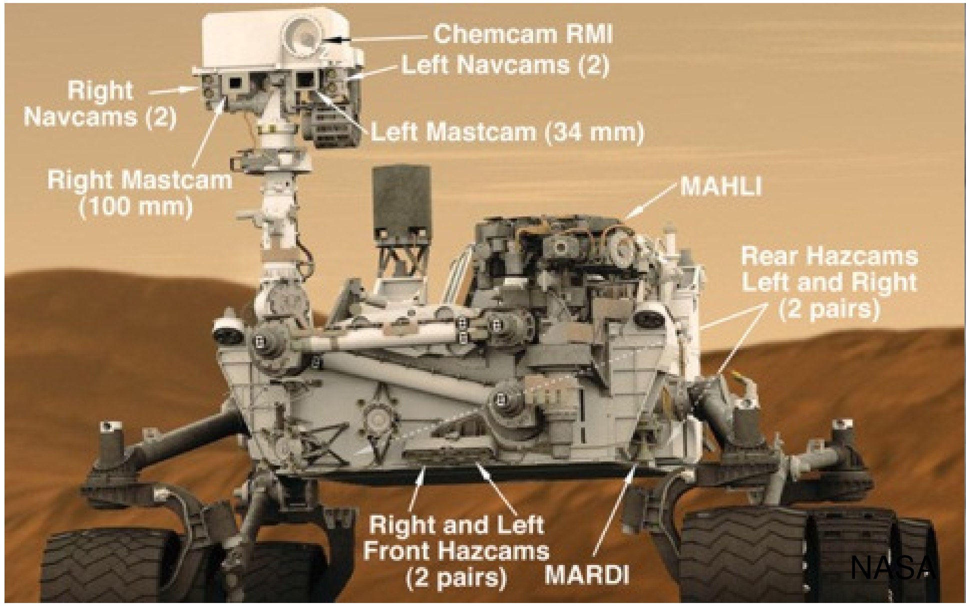
One day there will be more. There are geologists who are crazy enough to put on spacesuits and pretend to do field work in the desert, as a proxy for Mars.

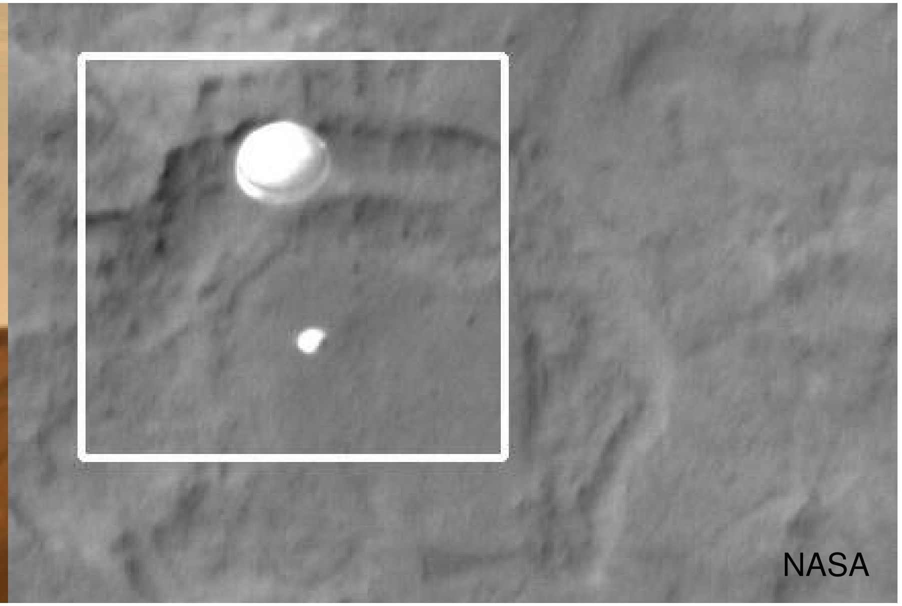


Images from NASA
http://marsrovers.jpl.nasa.gov/
gallery/spacecraft/images/

- NASA's twin robotic Mars Exploration Rovers, *Spirit* and *Opportunity (aka "oppy")*, landed on Mars January 4 and 25, 2004 in search of answers about the history of water on Mars. They were part of NASA's Mars Exploration Program. The results were totally amazing. We basically had geologists on Mars.

The Mars Rover *Curiosity* landed on August 05, 2012

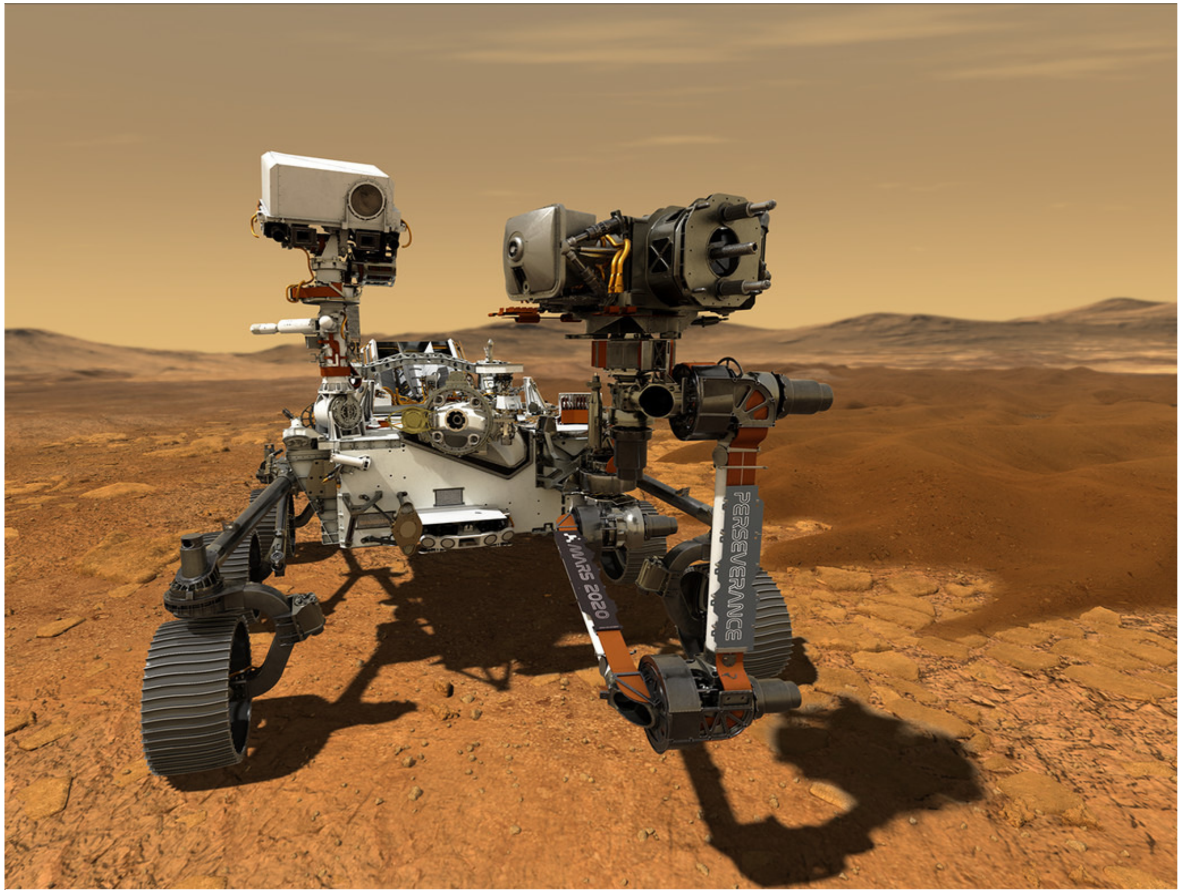




- Curiosity is exploring a specific region that shows evidence for ancient sedimentary rocks (suggesting water in the past).

- Instruments on these rovers allow simple analytical work to identify minerals and rocks, as well as the information from high-resolution digital imagery. Mars is a fascinating world, and perhaps the only place we might establish a foothold beyond Earth. It is a prime focus for Planetary research.

NASA

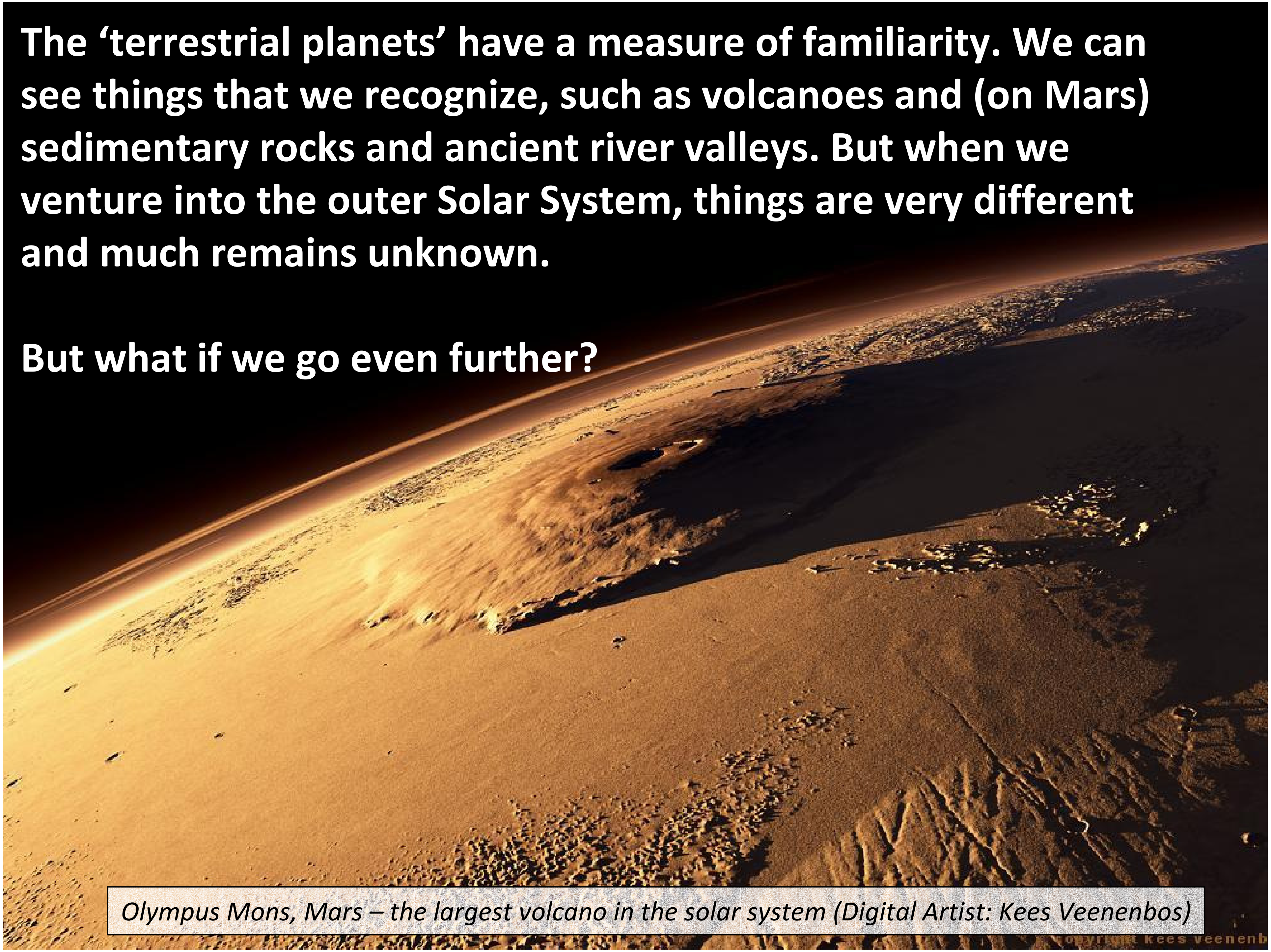


- 2021: Perseverance and Ingenuity take on a new Mars mission………A new generation of robotic explorers.

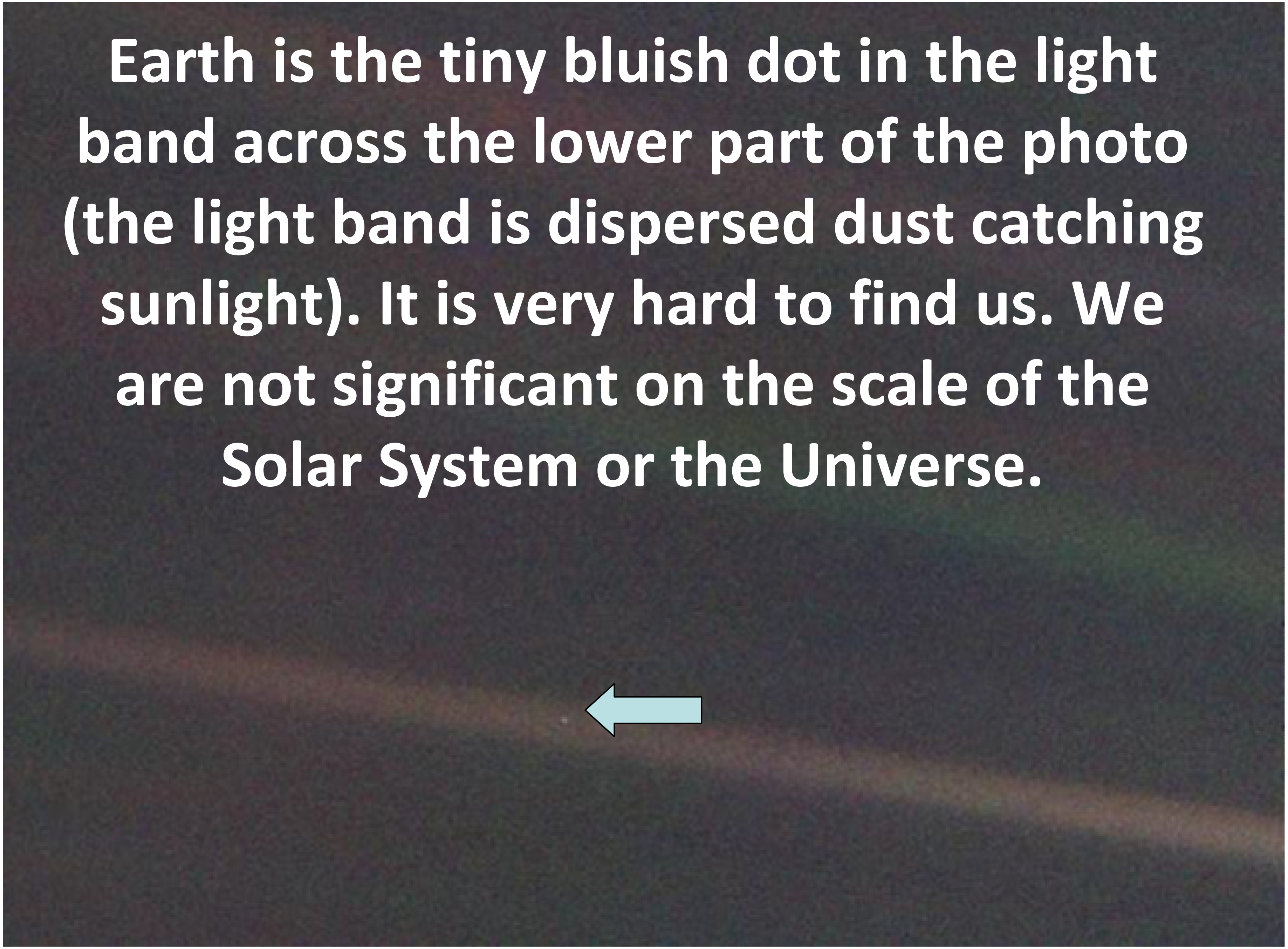
- Imagine! We built a helicopter that could fly in an atmosphere only a fraction of Earth’s thickness.

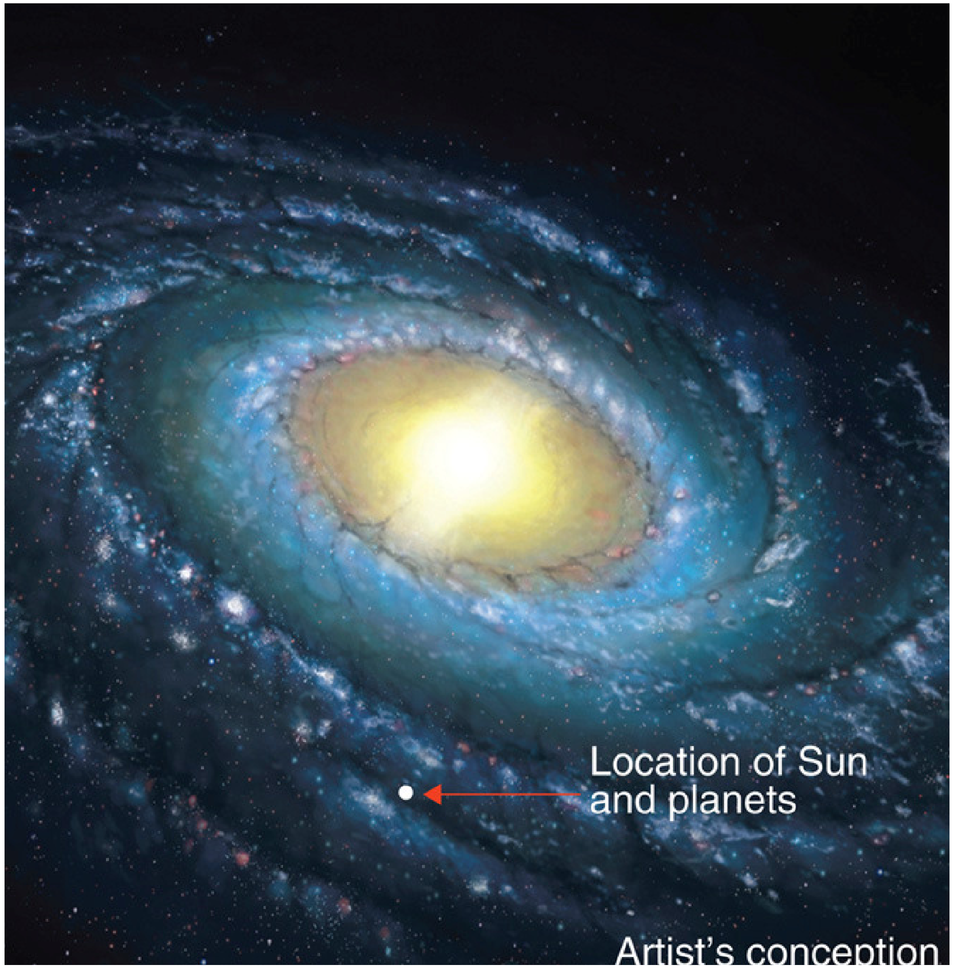
The ‘terrestrial planets’ have a measure of familiarity. We can see things that we recognize, such as volcanoes and (on Mars) sedimentary rocks and ancient river valleys. But when we venture into the outer Solar System, things are very different and much remains unknown.

But what if we go even further?

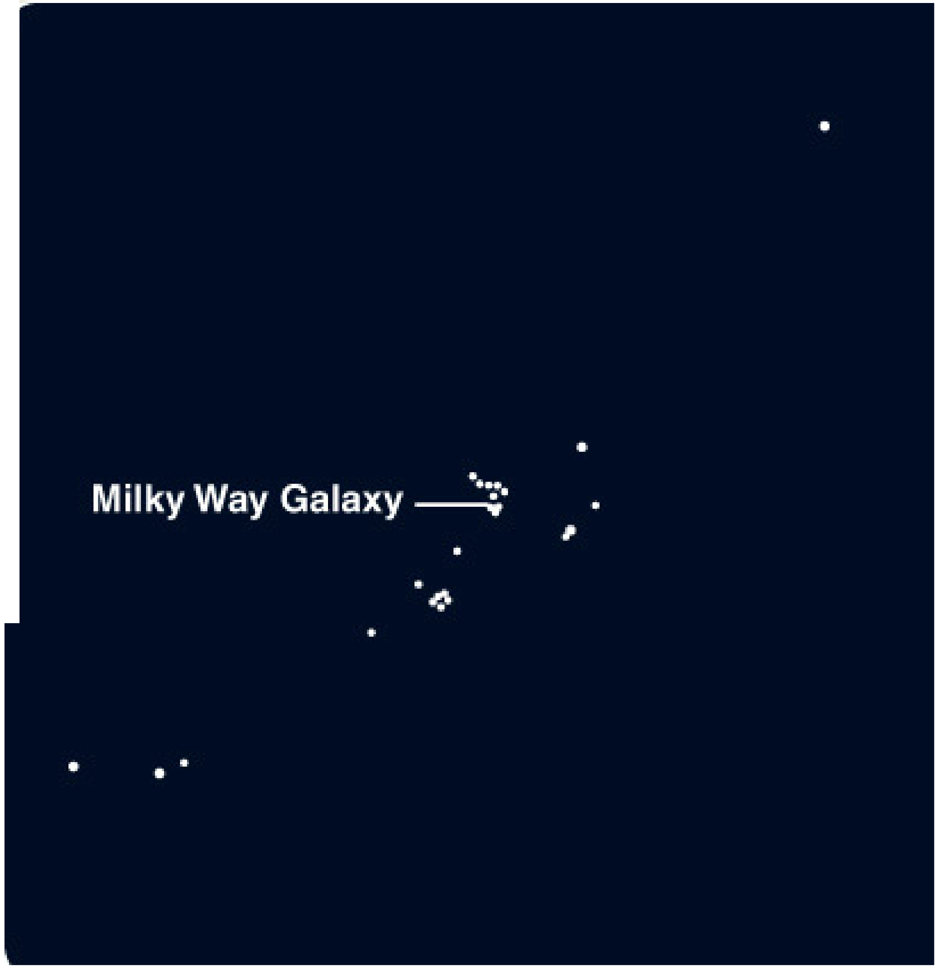


Olympus Mons, Mars – the largest volcano in the solar system (Digital Artist: Kees Veenenbos)

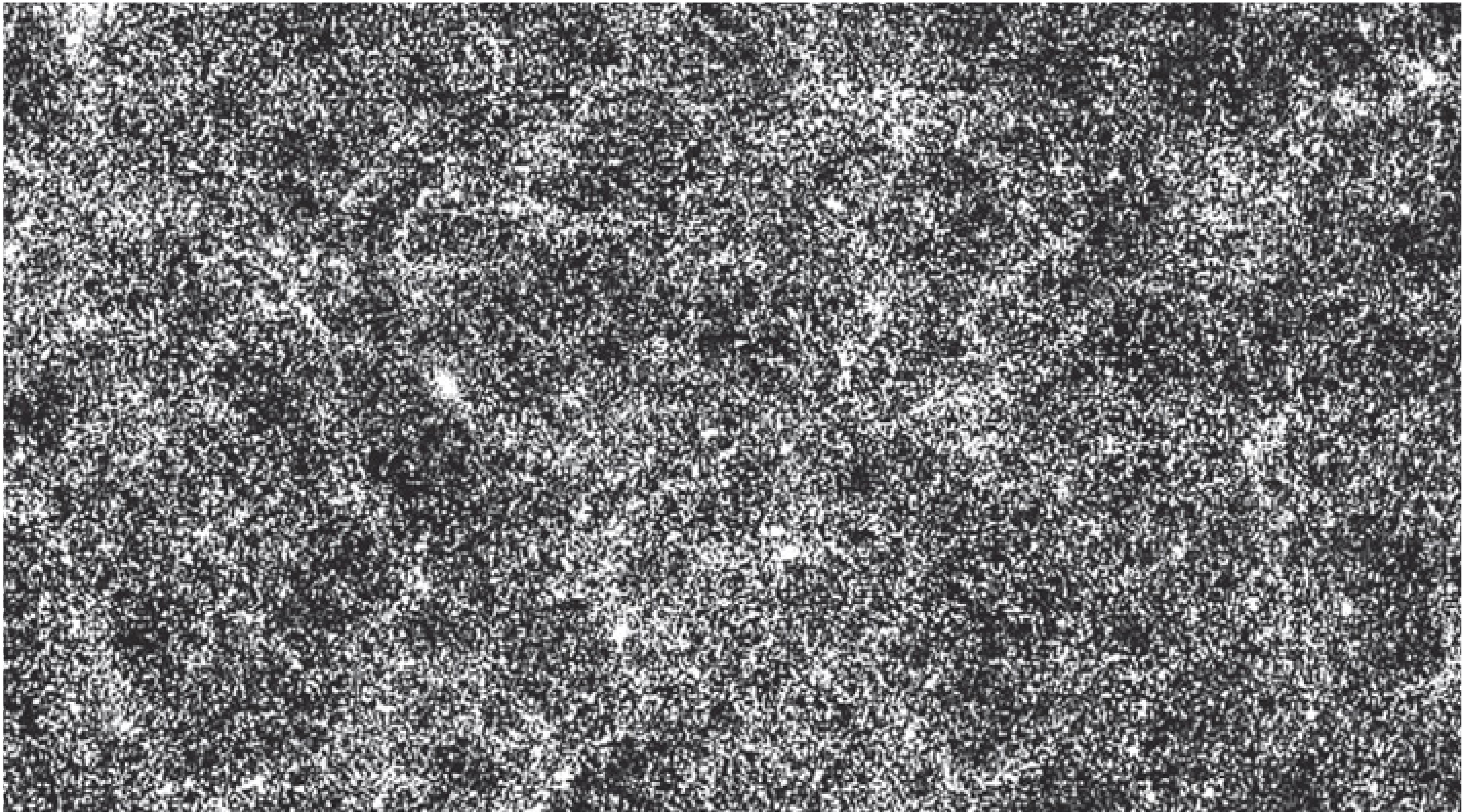

Earth is the tiny bluish dot in the light band across the lower part of the photo (the light band is dispersed dust catching sunlight). It is very hard to find us. We are not significant on the scale of the Solar System or the Universe.



- The nearest star is 4 light years from Earth. The Milky Way galaxy is at least 80,000 (8×10^4) LY across.....

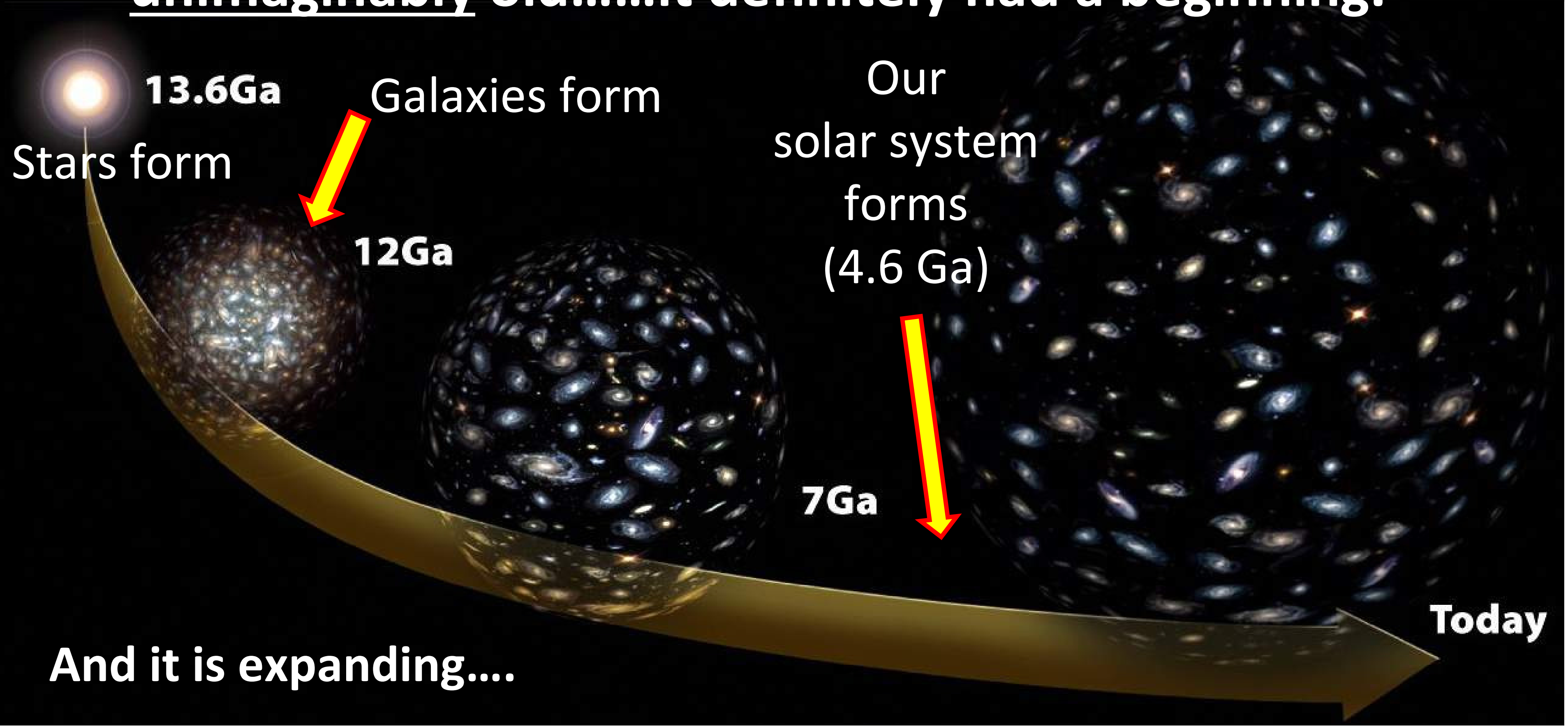


- We are part of a cluster of galaxies. Our nearest neighbour (Andromeda) is ~ 7 million (7×10^6) LY away from us........



But this is a tiny fragment of the Universe. This image shows the distribution of galaxies on an even larger scale, where they are clustered into bright areas and also filaments, with some regions of relatively low density. This occupies many billions of light years!

- **All of the mass and energy in the Universe was once packed into a single small point.**
- **It exploded at 13.7 Ga (13.7 billion years ago) and has been expanding ever since.**
- **Though the Universe is unimaginably big, it is not <u>unimaginably</u> old……it definitely had a beginning.**

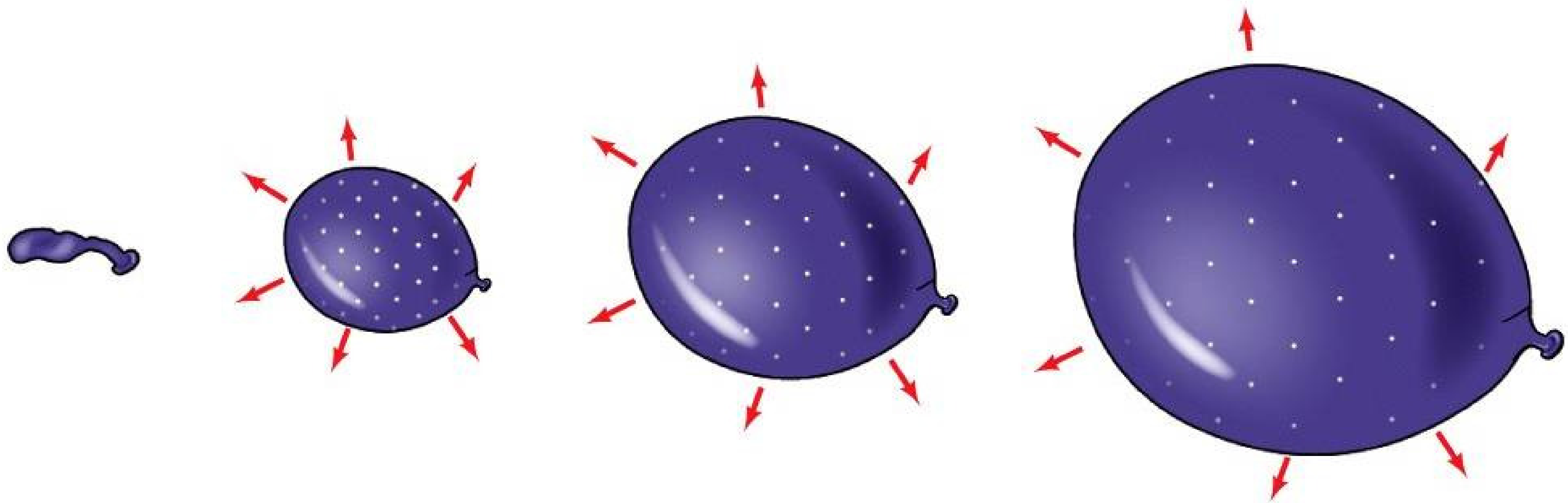


Edwin Hubble (1889-1953)

The 'Hubble Constant' is a measure of how fast the universe expands, and you've all heard of the Hubble Telescope.

- Edwin Hubble is often called the 'father of cosmology'.
- However, he is best known for having truly established the reality of an expanding universe. He did this by using the subtle measurements of emitted radiation from distant galaxies (to be discussed more later).
- Hubble showed that other galaxies were moving away from ours, and that the further they were from us, the faster they were receding.

Expanding Universe: Balloon Analogy



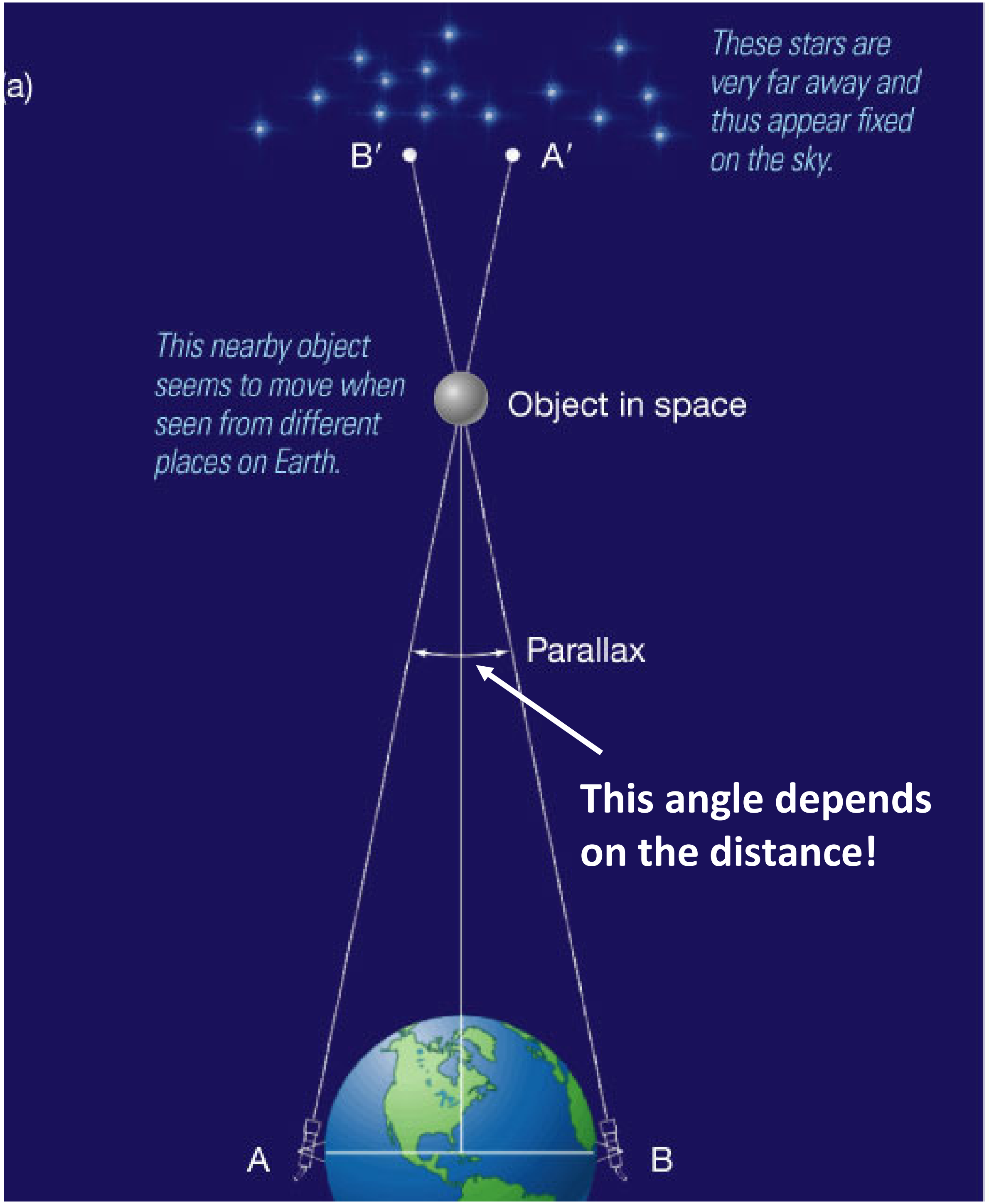
- The ‘Balloon Analogy’ is commonly used. Imagine how a balloon expands; with time individual points on the surface of the balloon (or within it if it were solid) will continue to move apart.

- So, back to our neighborhood in the Milky Way. Enough of cosmology, for now. The Universe contains different types of stars, and their lifespans vary. Luckily for us, ours is long-lived.

- We know that the Sun formed about 4.6 Ga, and it's about half-way thru its life. The Solar System and the Sun formed at the same time, and both have evolved over time. Details are for later.

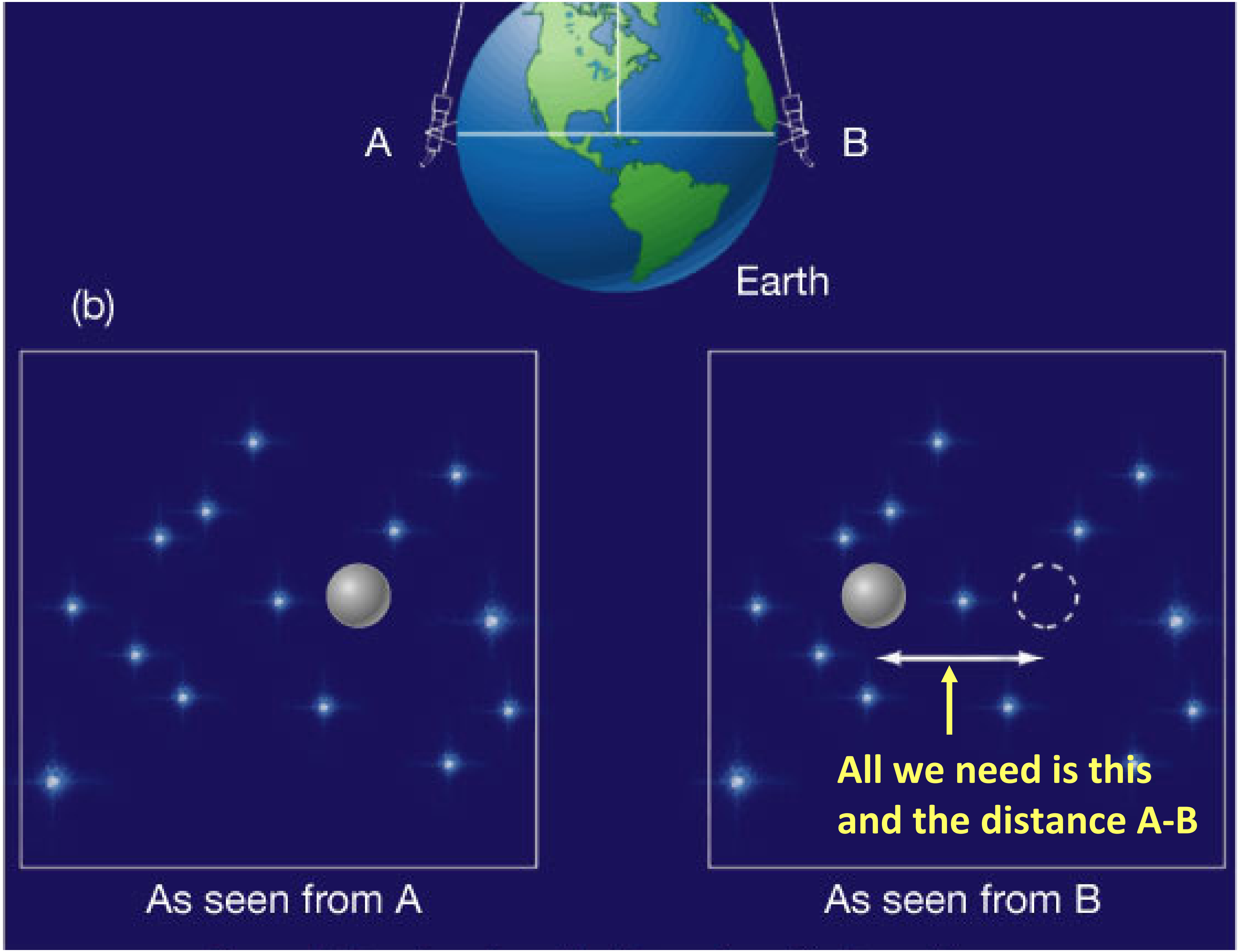
Note that in this image we clearly see the varied colours of stars. Also, we see variations in brightness – and also apparent size.

Globular Star Cluster M15 – About 33,000 Light Years from Earth and containing at least 1 million stars of various types – Hubble Image



How Far Away?

- If we observe some object from two locations – on either side of the Earth – at the same time - its angular position is different.
- From this, we make an imaginary triangle, and if we know the distance between the points, we can make two right-angle triangles.

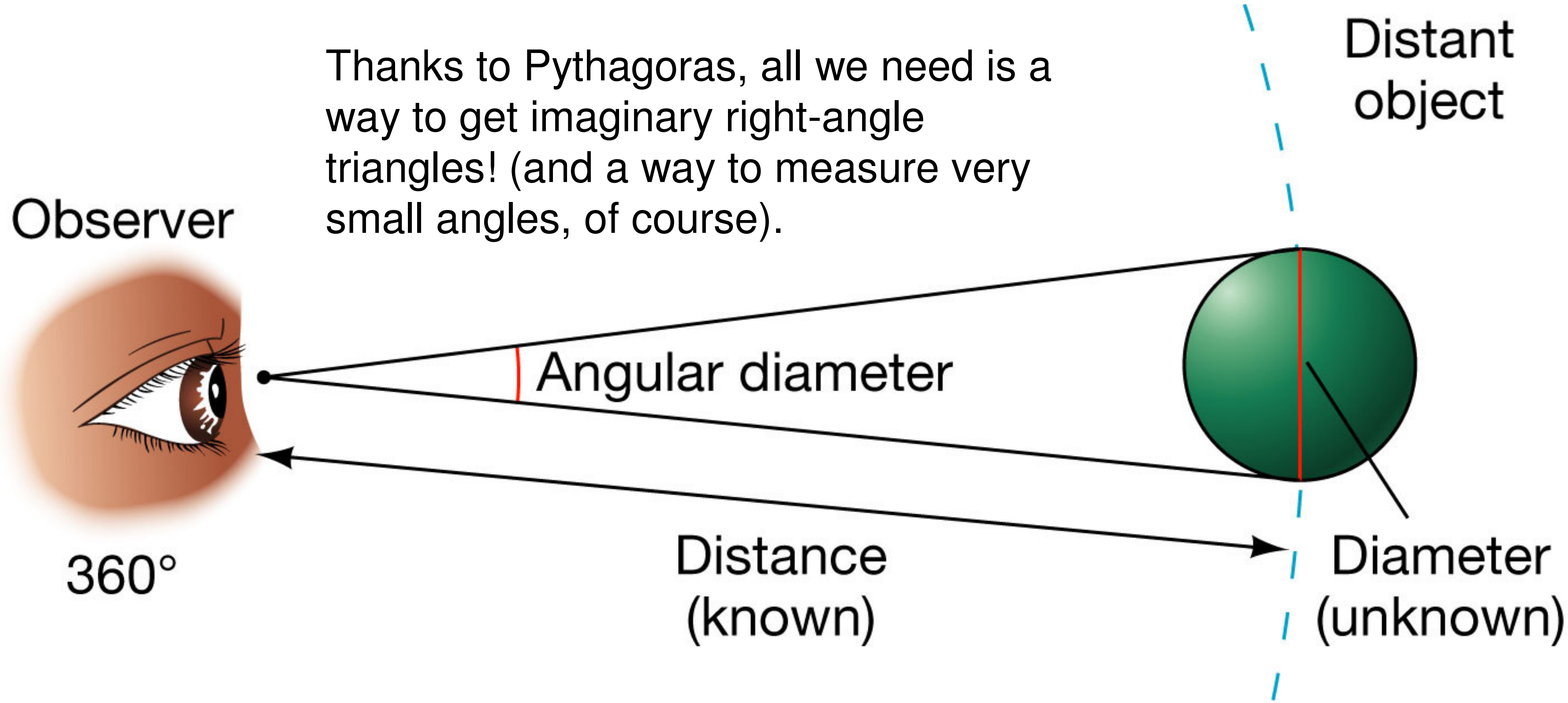

A
B
Earth
(b)
As seen from A
As seen from B
All we need is this
and the distance A-B

Parallax Angles and Distance

- For solar system objects, we can use measurements from different points on the Earth's surface – the longest baseline is then the diameter of the Earth.
- For stellar measurements, we need a much longer baseline, so we use measurements taken about 6 months apart, when the Earth is on opposite sides of the Sun. Then the baseline is 3×10^6 km (2 AU).
- A star 3.2 LY away has a Parallax Angle of 1 second – which is where the term **Parsec** comes from.
- For **very** distant objects like some galaxies, angles are too small. But there are other spectroscopic methods (EM radiation) that can be used.

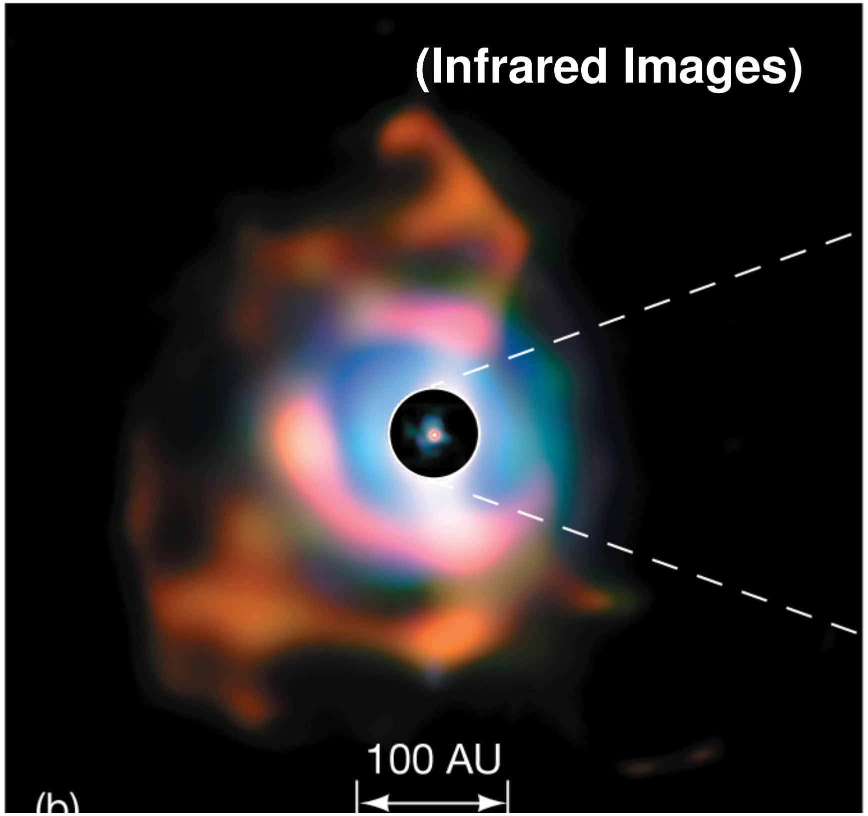
Distance and the 'Small Angle Formula'

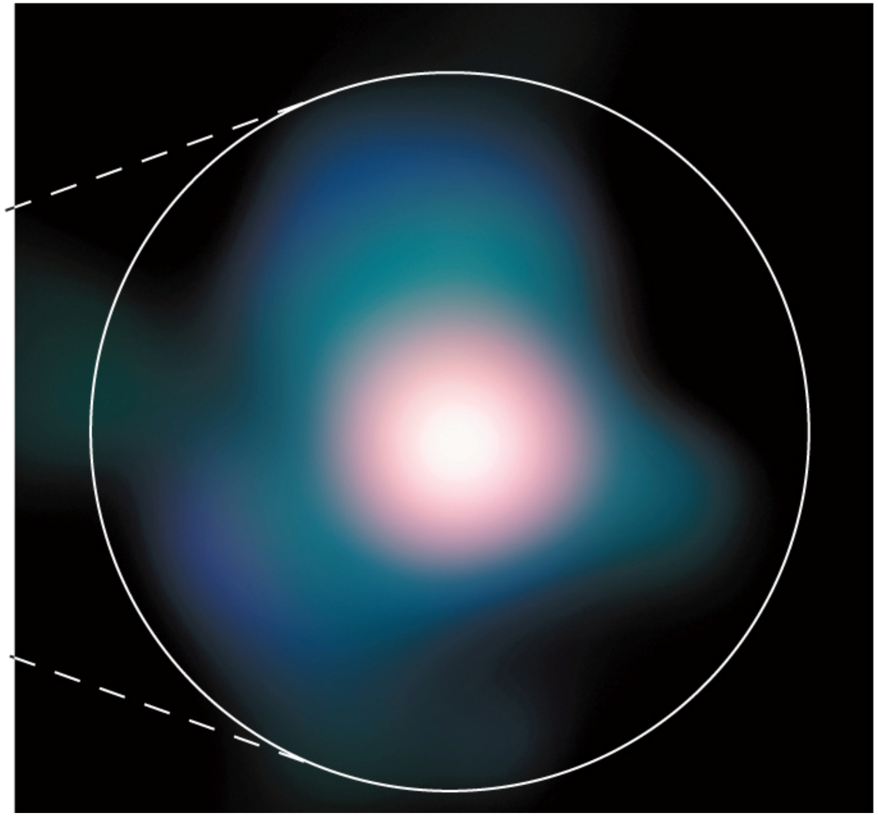
Thanks to Pythagoras, all we need is a way to get imaginary right-angle triangles! (and a way to measure very small angles, of course).



- **The 'angular diameter' of an object is a function of its real size and its distance. If we know how big an object is, we can obtain the distance without parallax. If we know the distance, we can calculate the size. As the angles are always small, the formula is simple.**

Star Betelgeuse – The Ultimate Supergiant

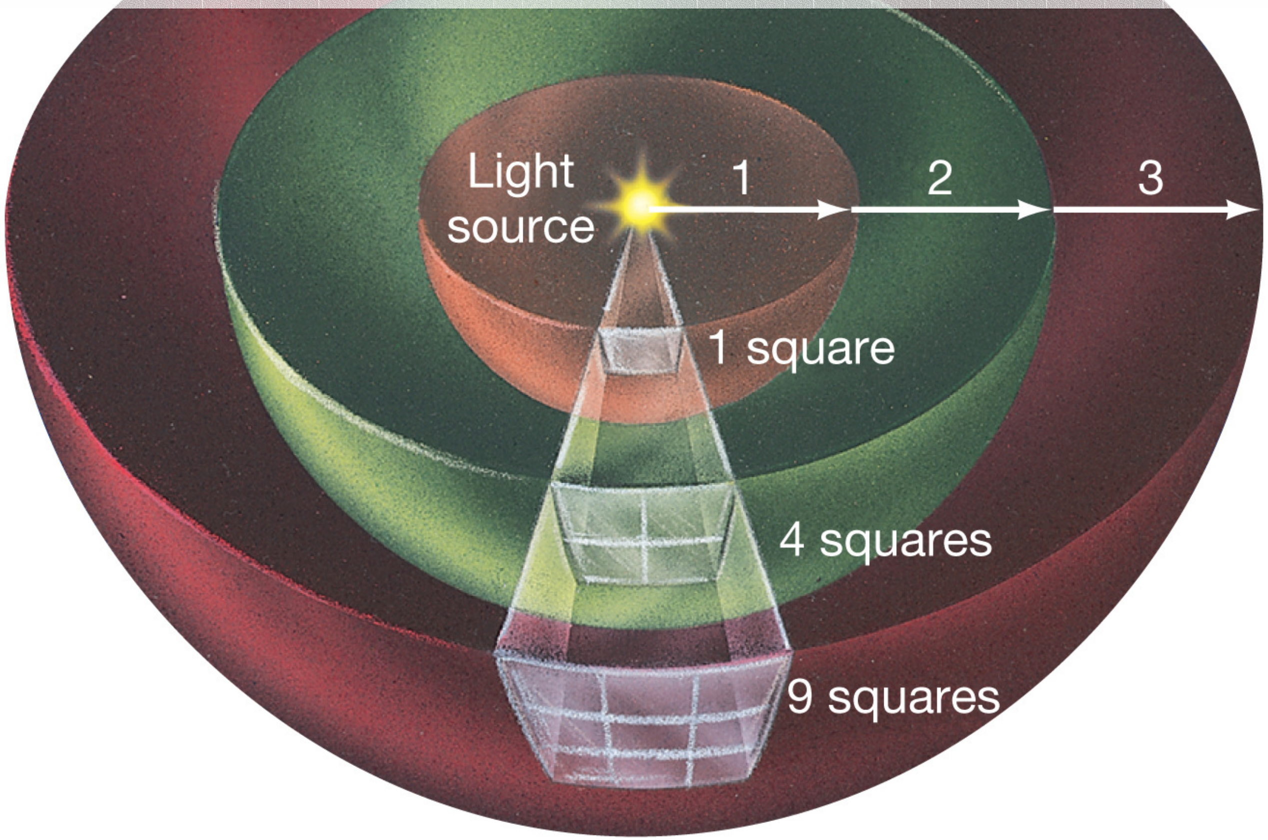




- **Very large stars can be 'sized' directly using their apparent size and distance – especially using space telescopes. Betelgeuse, in Orion, is 600 times larger than the Sun, so its outer limit is much larger than Earth's orbit. Smaller stars are harder to measure….**

Figure 17.5

The Inverse Square Law – A Universal Truth (this appears time and time again in physics)

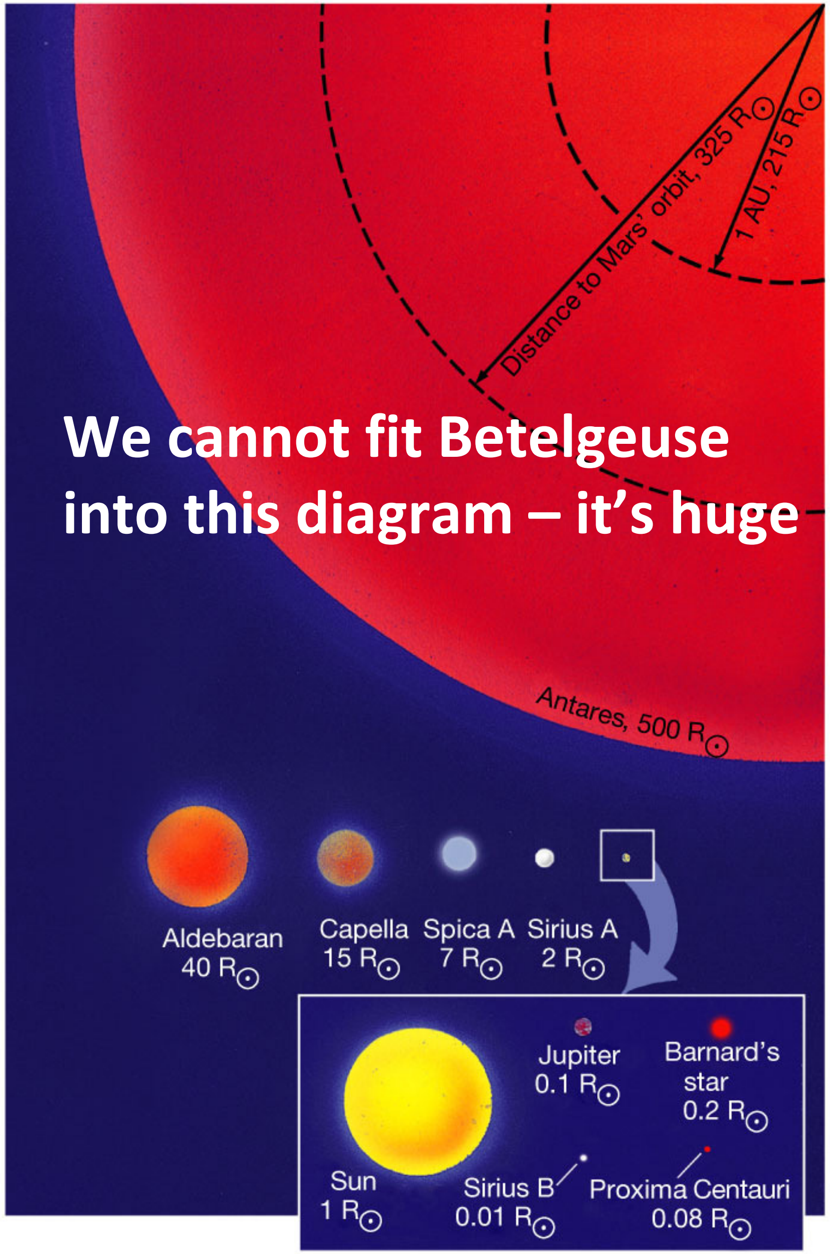


- The energy output from a star – or any object that emits EM follows the inverse square rule; if you double the distance, it diminishes by a factor of 4 (2^2)l if you triple the distance, it diminshes by a factor of 9 (3^2). And so on and so on and so on.

Information from Starlight – Vital!

- All stars – like the Sun – produce vast amounts of electromagnetic energy.
- The intensity of such radiation diminishes with distance; we know this intuitively. But there are rules!
- If we know how **far away** a star is and how **bright** it is, we can estimate luminosity (energy it yields). This also has a relationship to size – more star, more energy.
- The wavelength 'spectrum' for any object that emits EM energy gives us its temperature (we'll discuss this later on). So we can estimate temperatures of stars.
- By observing the behaviour of "binary" stars – where one orbits another – we can get estimates of mass.

How Big are Stars? – They Vary a Great Deal



- We have ways of estimating the size/mass of stars and their energy outputs. Stars vary greatly in size. Here are some examples, compared to the Sun.

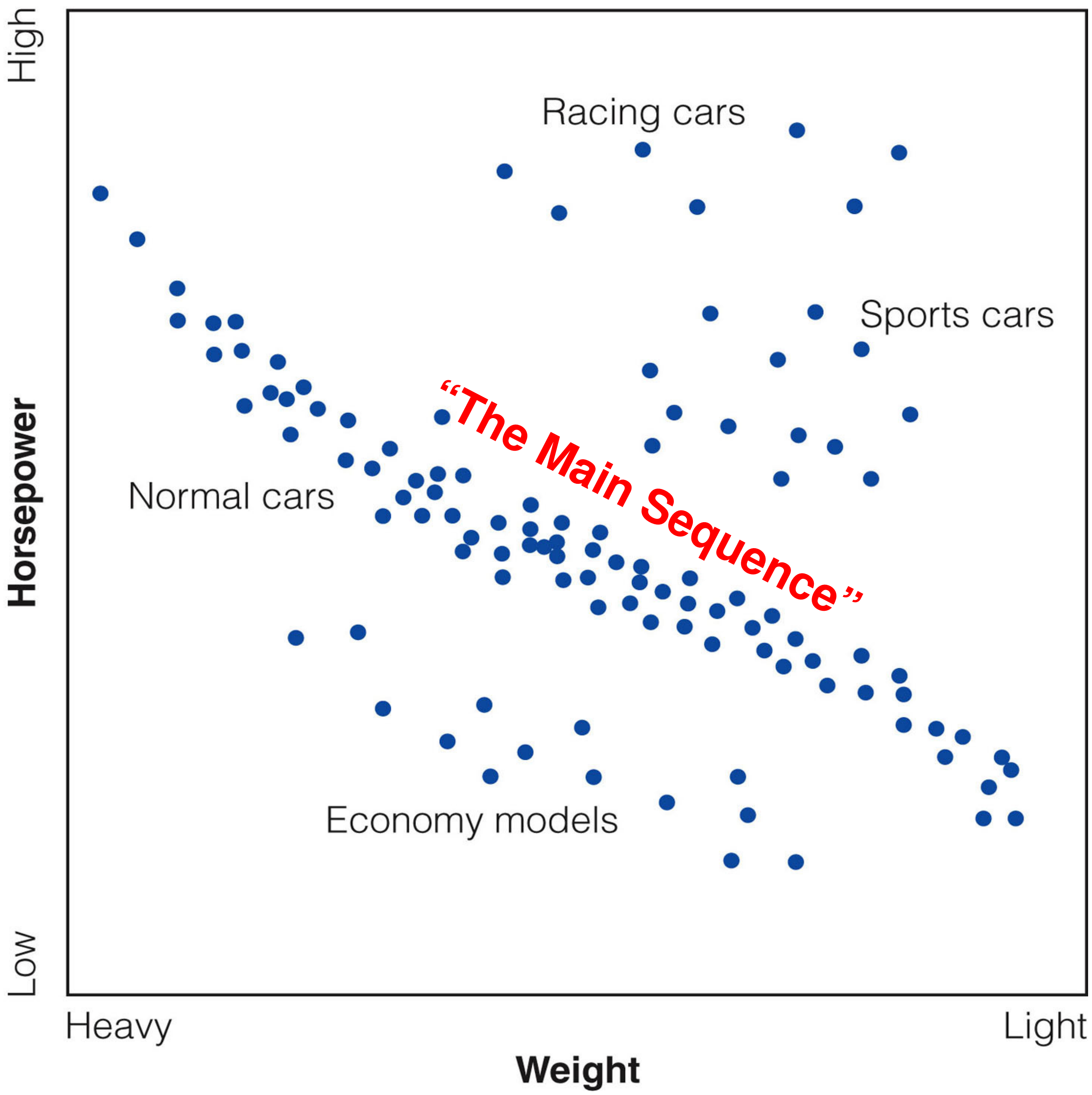
- Some are much larger, but others are small – most are smaller than the Sun.

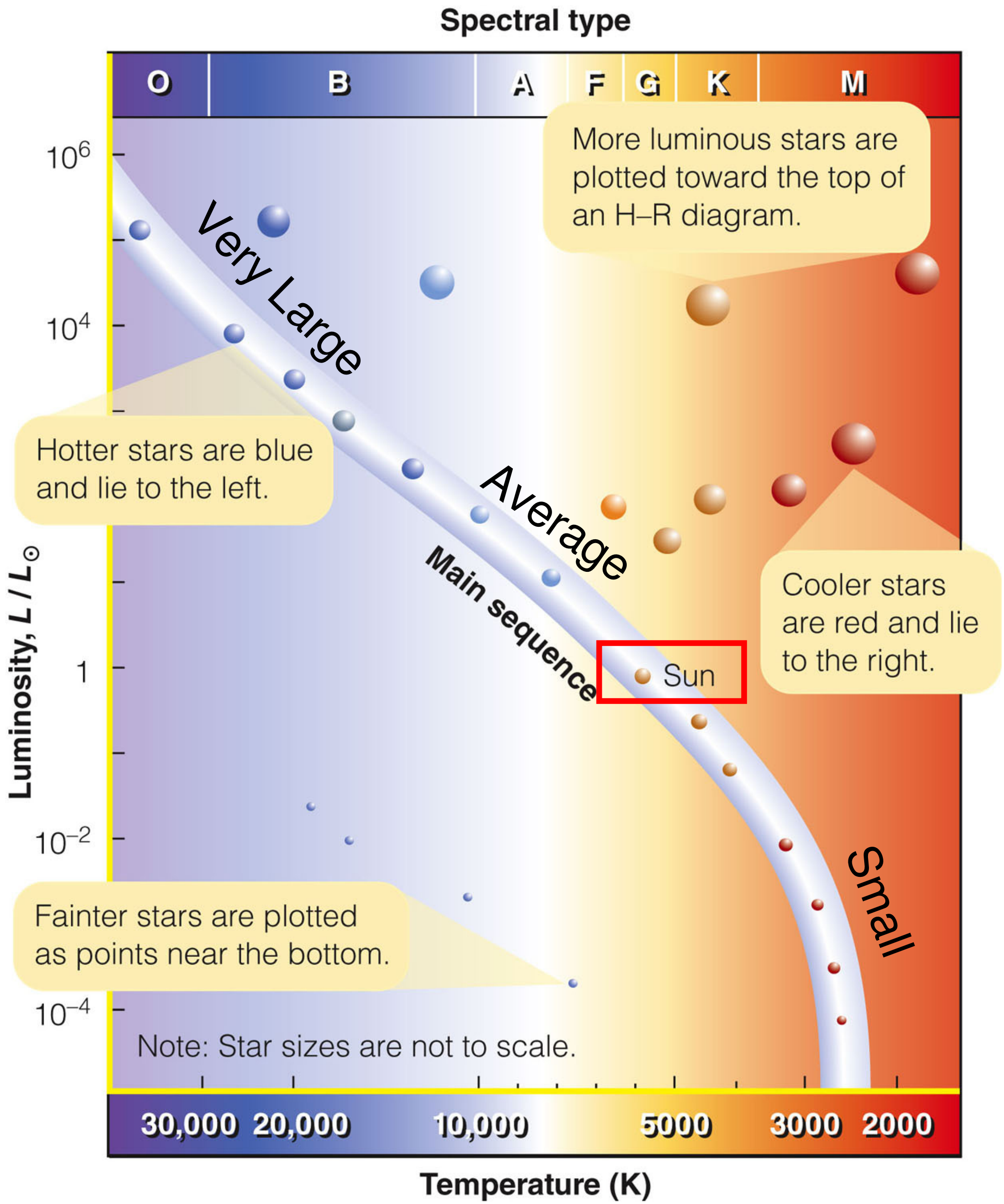
- From these various parameters, we can classify the populations of stars, and understand how they evolve.

Your text has an interesting chart that simulates what we find.

Imagine plotting power vs weight for cars. Most of them will define a narrow band – bigger cars need more power.

But some special types will plot off this bulk trend…





- Within the main sequence, mass and temperature are linked closely.

- We can also figure out the sizes (mass) of stars and their temperatures.

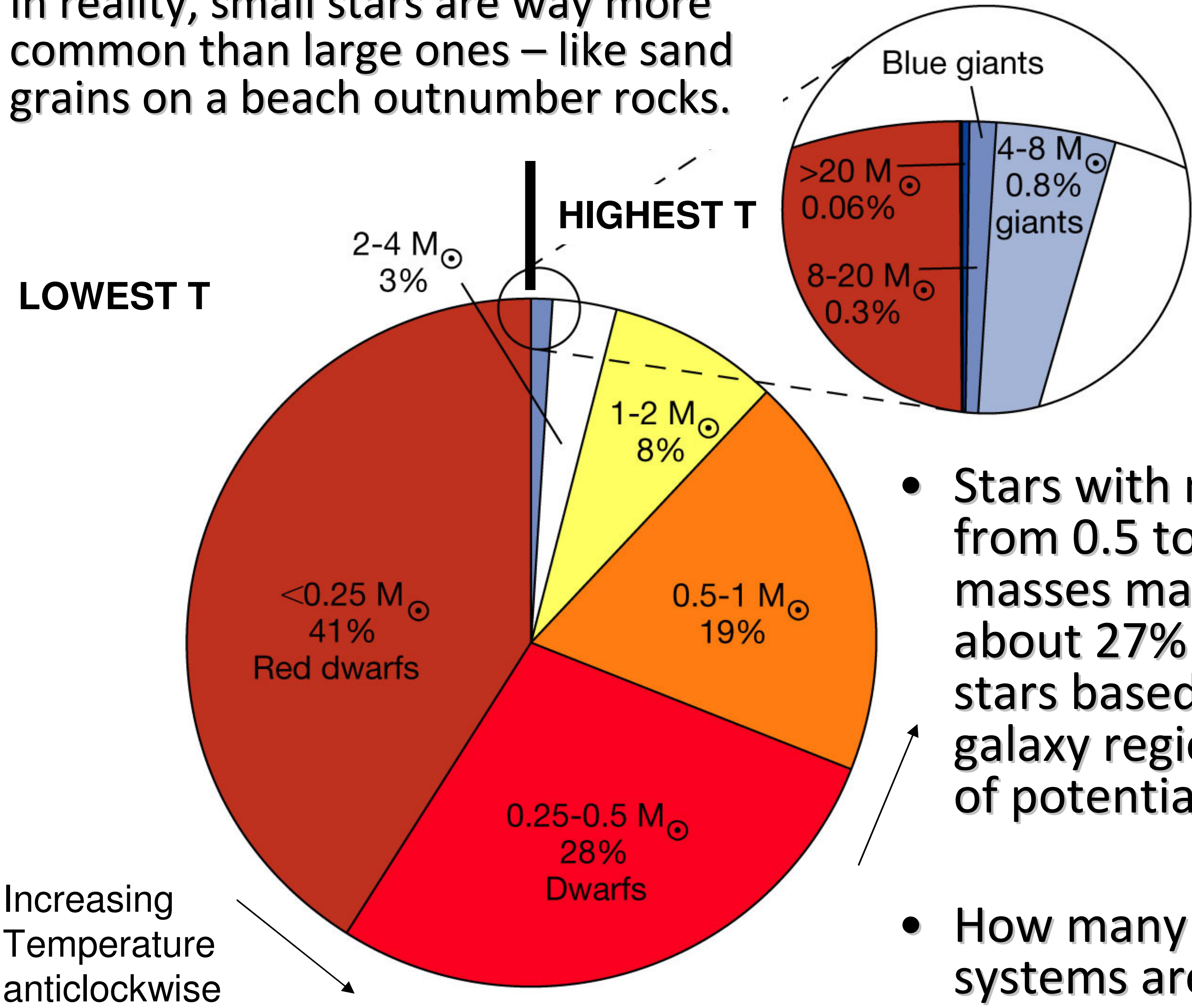
- It turns out that the **Main Sequence** is defined mostly by the Mass of stars.

- Hot, luminous stars are mostly bigger than the Sun. But what does this really mean?

Good Stars and Bad Stars……

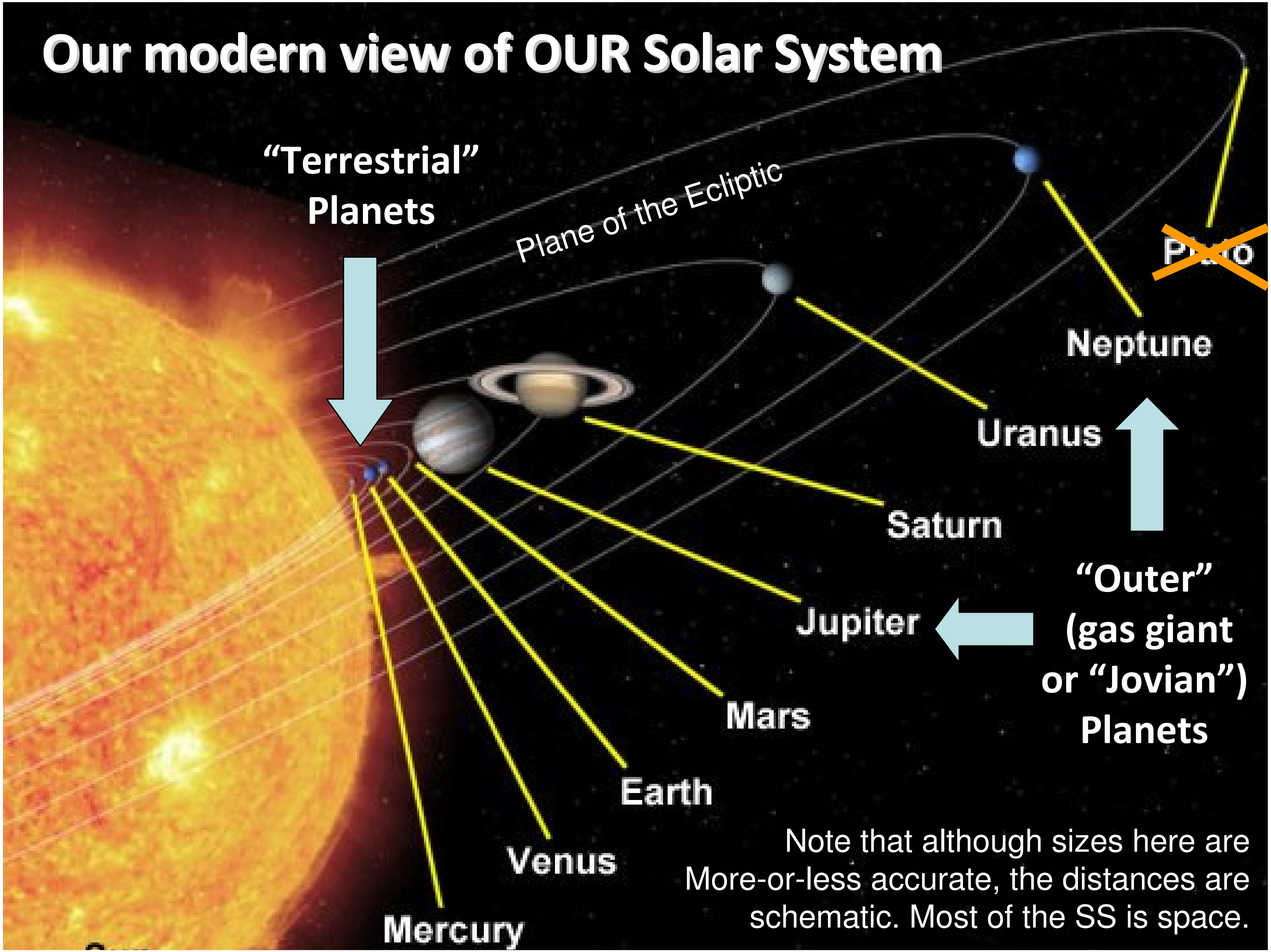
- In general, the massive hot stars are unsuitable candidates for habitable planets, as they emit lots of nasty radiation. More importantly, they have short life spans (< 100 m.y.). Not much time for evolution!!
- They run out of hydrogen fuel, shift to more energetic fusion reactions, and then they explode as “Novas”.
- Dwarf stars are extremely long-lived, but because they are so small and dim, they will only have a narrow ‘habitable zone’ in which life might be able to exist.
- Many stars are in binary systems – again, these are likely not the best for stable planetary orbits.
- But the good news is that stars like the Sun are ***very common*** on the scale of the Universe……

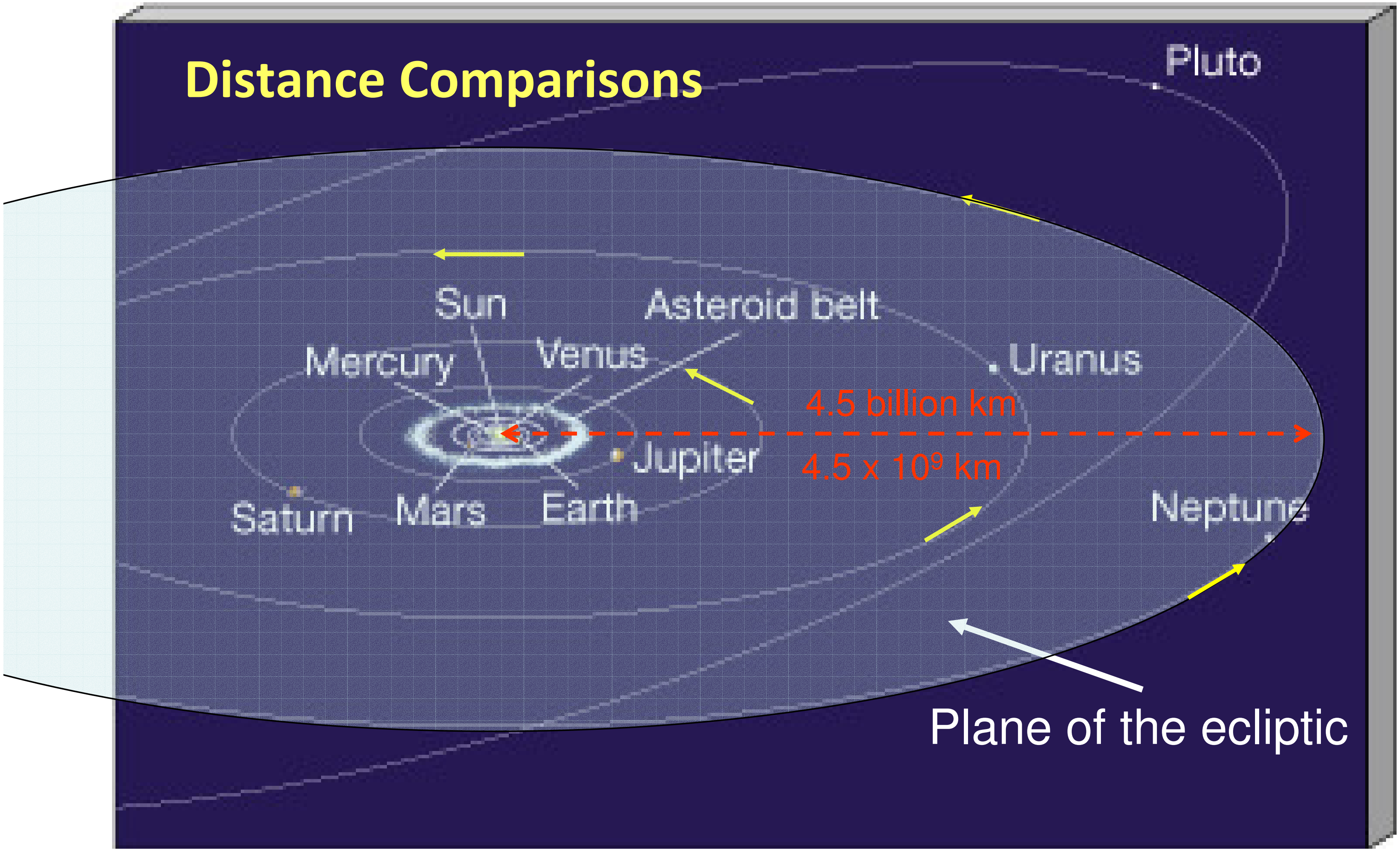
- In reality, small stars are way more common than large ones – like sand grains on a beach outnumber rocks.



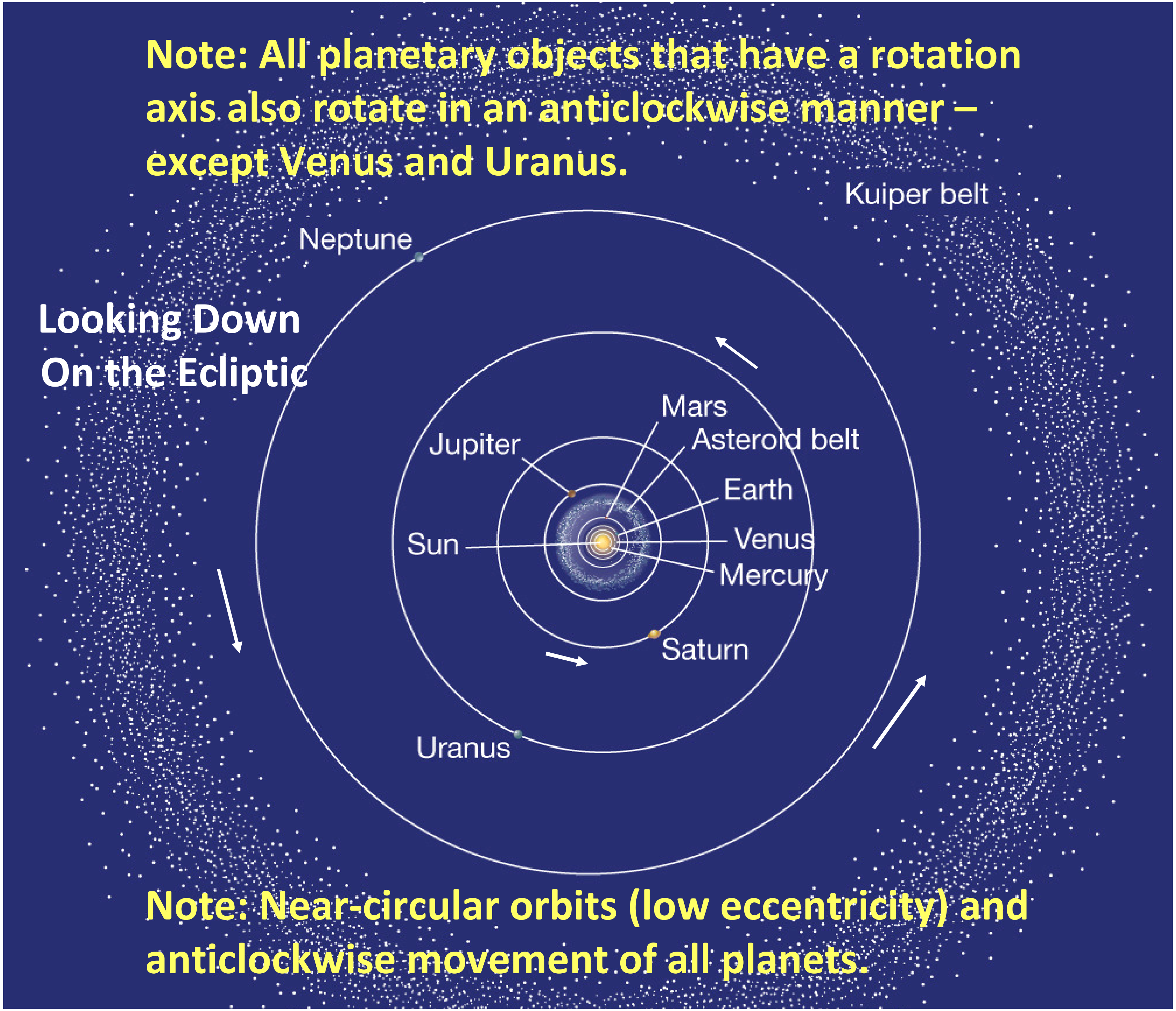
- Stars with masses from 0.5 to 2 solar masses make up about 27% of all stars based on our galaxy region. Lots of potential.....

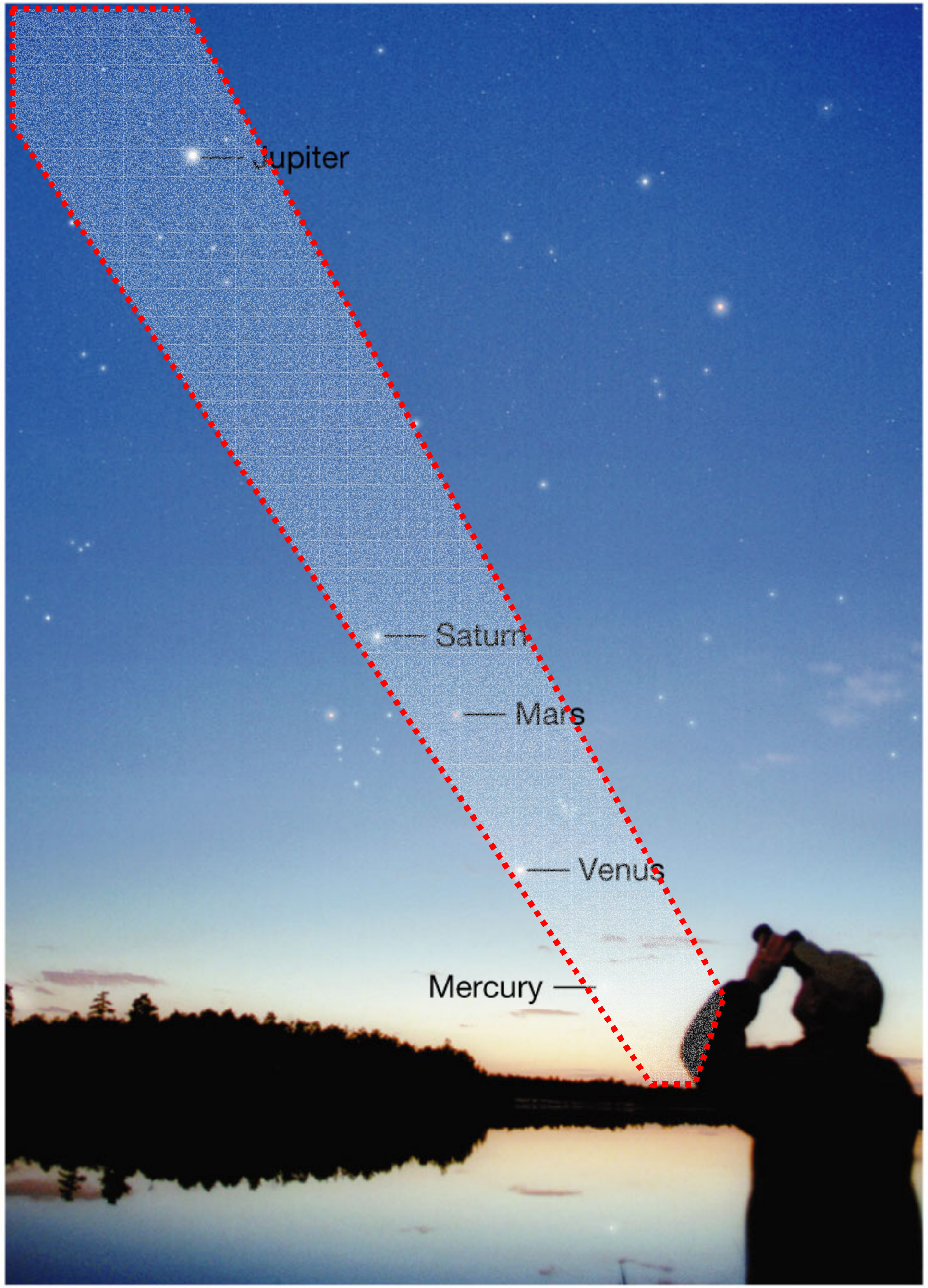
- How many solar systems are there?


Our modern view of OUR Solar System
"Terrestrial"
Planets
Plane of the Ecliptic
Pluto
Neptune
Uranus
Saturn
Jupiter
"Outer"
(gas giant
or "Jovian")
Planets
Mars
Earth
Venus
Mercury
Note that although sizes here are
More-or-less accurate, the distances are
schematic. Most of the SS is space.



This diagram gives an idea of how spread out the system really is. On the scale of Neptune's orbit, the Sun is tiny and the planets would be invisibly small. Note how Pluto is well outside the Ecliptic.


Note: All planetary objects that have a rotation axis also rotate in an anticlockwise manner – except Venus and Uranus.
Kuiper belt
Neptune
Looking Down
On the Ecliptic
Mars
Asteroid belt
Jupiter
Earth
Sun
Venus
Mercury
Saturn
Uranus
Note: Near-circular orbits (low eccentricity) and anticlockwise movement of all planets.



Seeing the Ecliptic

- This is the plane that includes the Earth's orbit. It is also the general plane within which all the planets move – it would be like an arch in the sky, but not located directly overhead.
- **This photo shows a rare planetary alignment in 2002, when five of the planets were all visible.**
- This means that all five were more-or-less around a line connecting the Earth to Saturn. This does not occur very often.