ASTR 1P01

Brock University
Prof. Barak Shoshany

Lecture 7: Astronomical phenomena on Earth

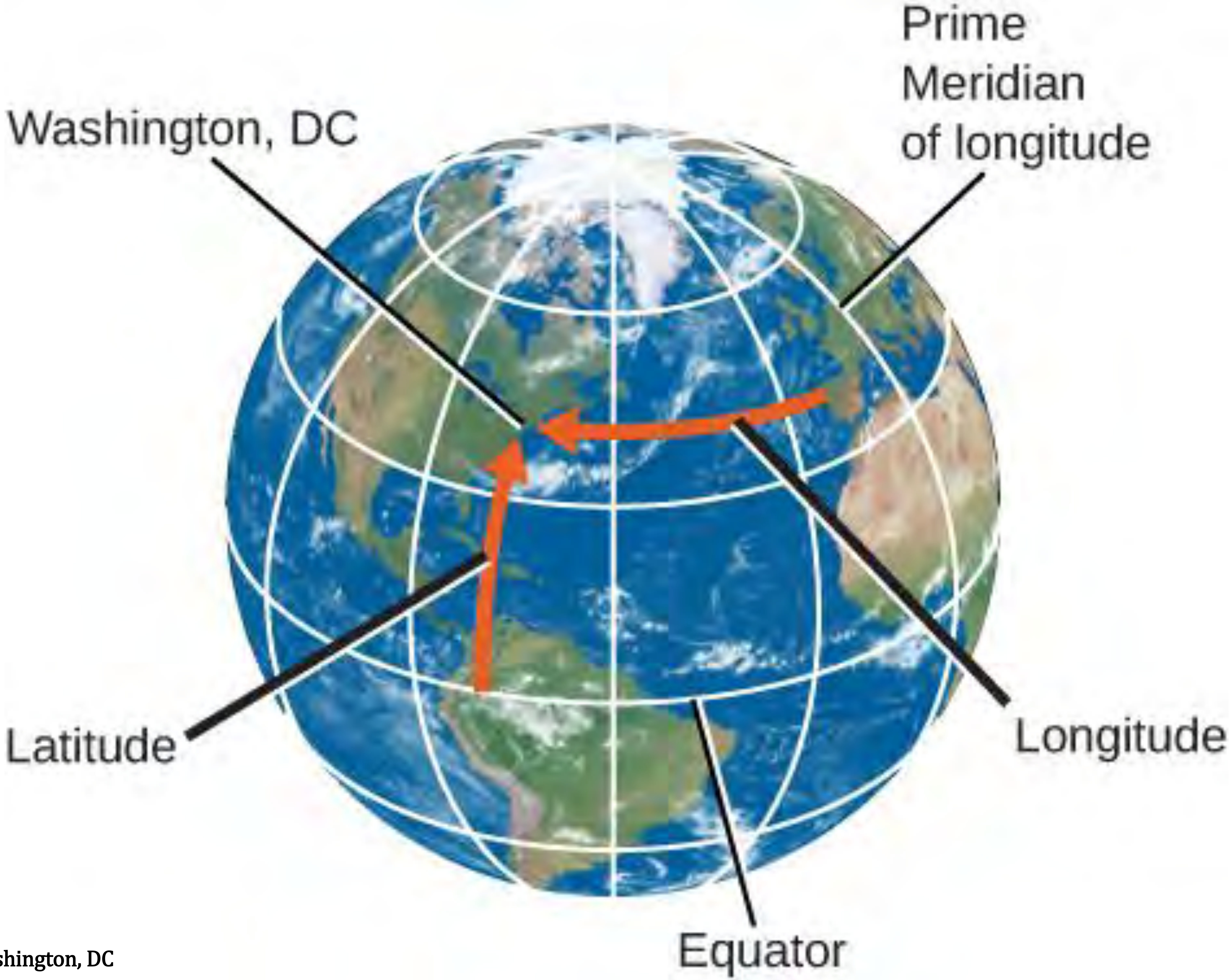
We will learn about…

- How to identify locations in the sky.
- Evidence for the rotation of the Earth.
- What causes the seasons.
- How days, years, and calendars are defined.
- Phases of the Moon.
- What causes the tides.
- Solar and lunar eclipses.

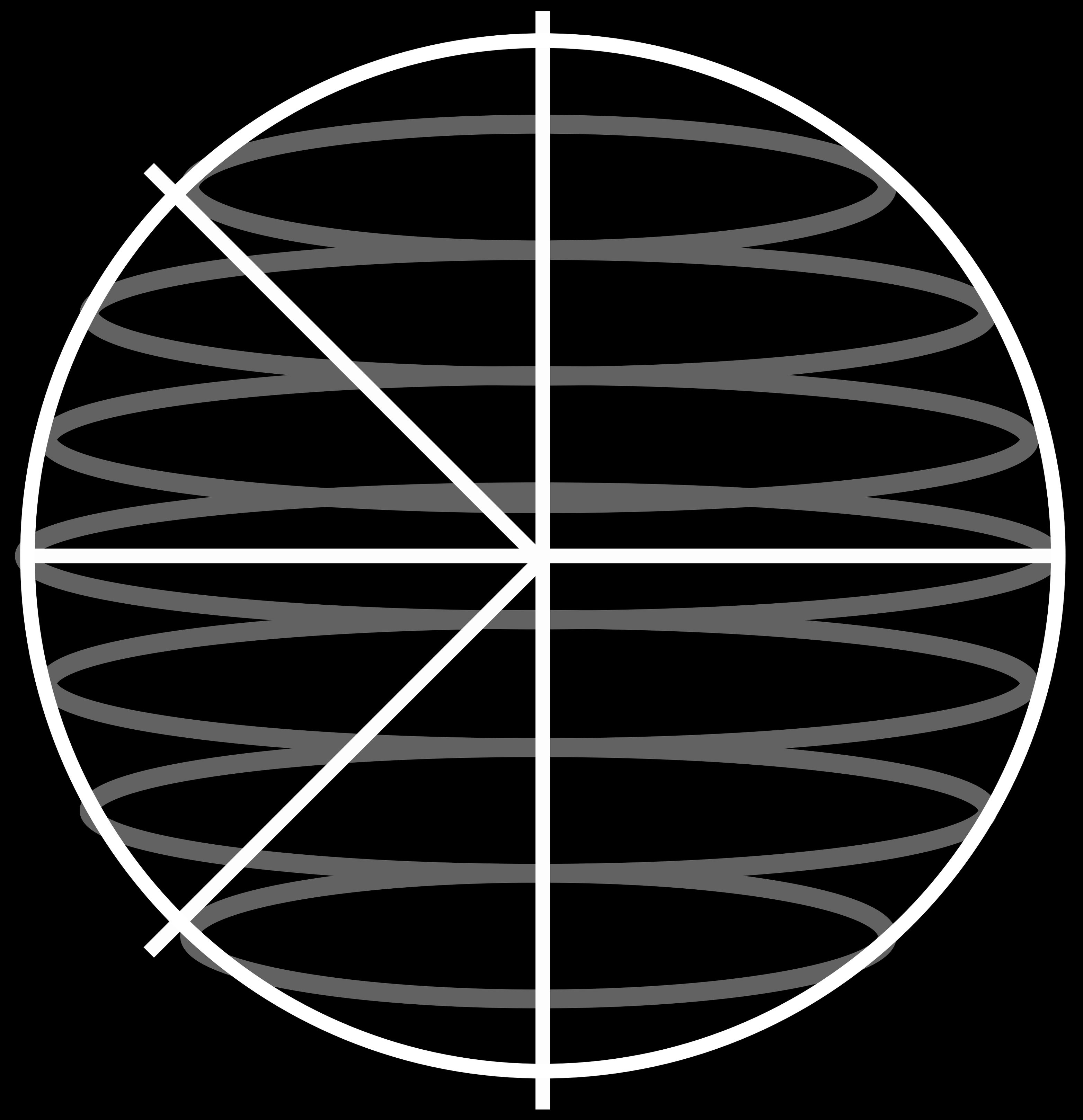
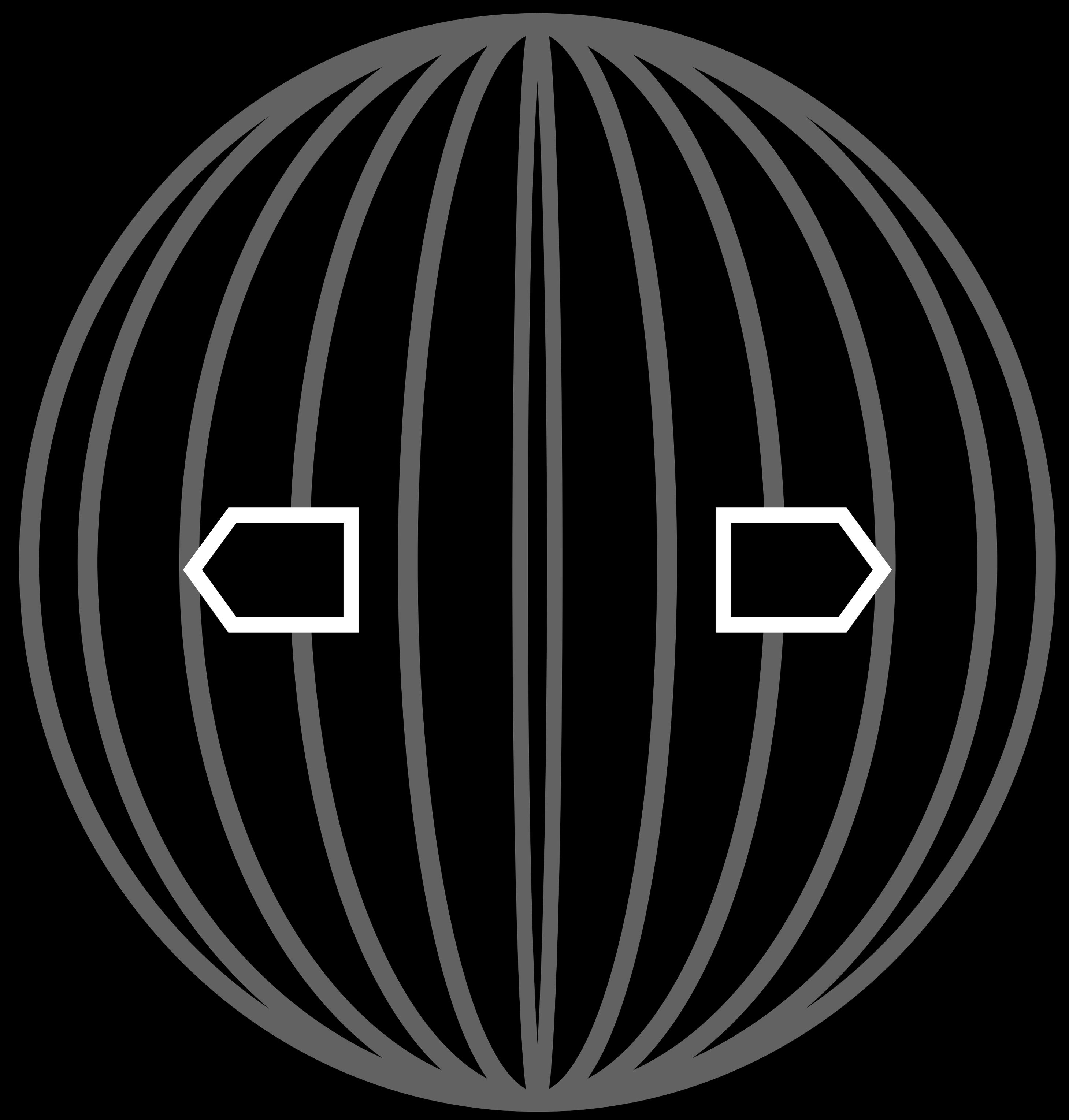
Planet Earth
Credits: NASA

Coordinates in the sky

- Let's recall the definition of latitude and longitude.
- The latitude of a point on Earth's surface is the angle it makes with the equator, to the north or south.
- A great circle is a circle with the same radius as the Earth.
- A meridian is a great circle that passes through the poles.
- The prime meridian is the meridian that passes through the Royal Observatory in Greenwich, England.
- The longitude of a point on Earth's surface is the angle it makes with the prime meridian, to the west or east.



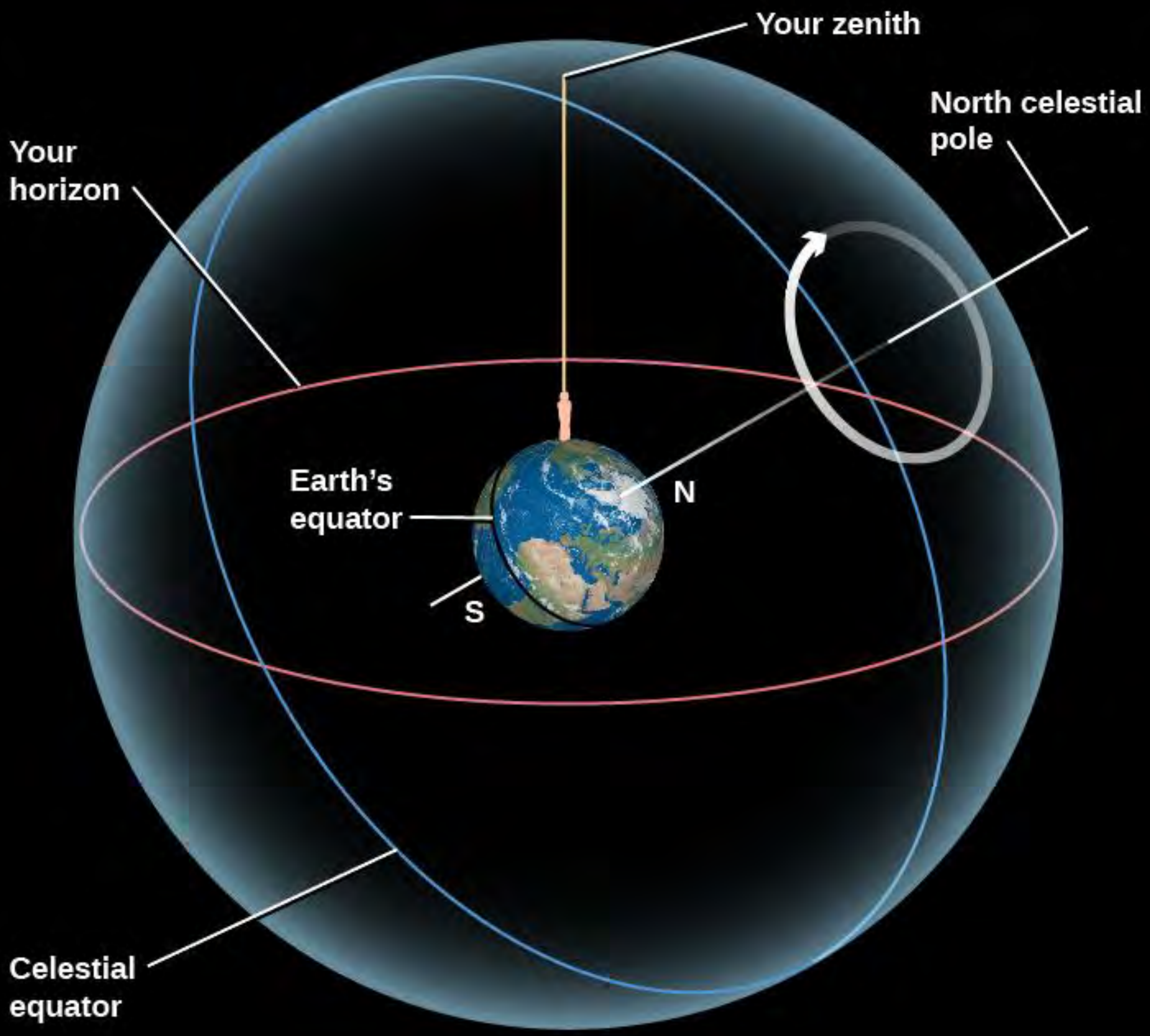
Latitude and Longitude of Washington, DC
Credits: OpenStax Astronomy

Latitude and Longitude
Credits: Found on Wikipedia, author unknown

Coordinates in the sky

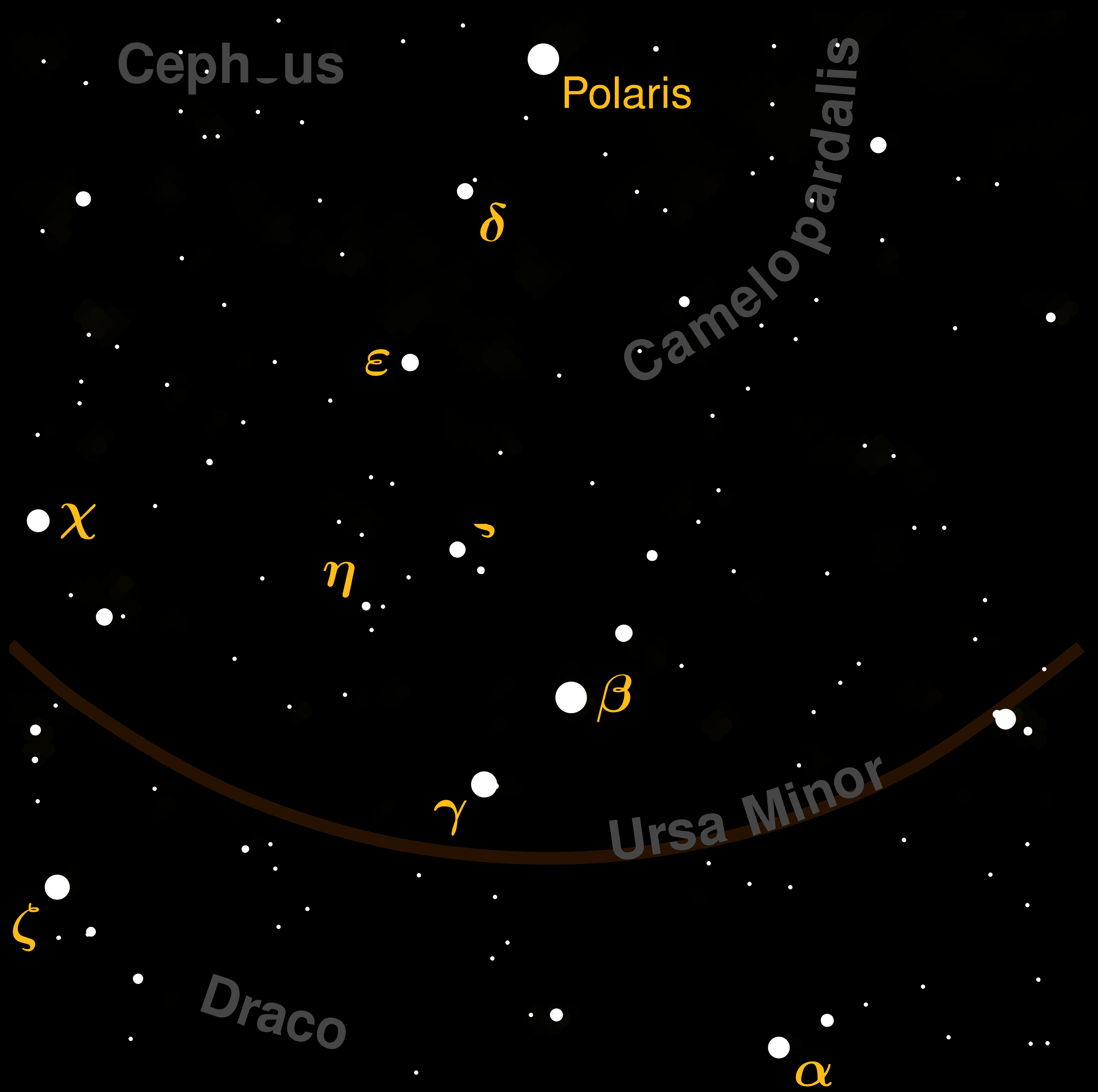
- Positions in the sky are measured using declination and right ascension instead of latitude and longitude.
- Declination is like latitude: the angle north or south relative to the celestial equator.
  - The celestial equator is the circle in the sky above the equator. It has declination 0°.
  - The north and south celestial poles are the points in the sky above the poles. They have declination +90° (north) and −90° (south).
- Useful mnemonic:
  - Latitude → altitude (height)
  - Declination → decline (decreasing height)
  - North is up on a map, so "height" indicates the north-south position.

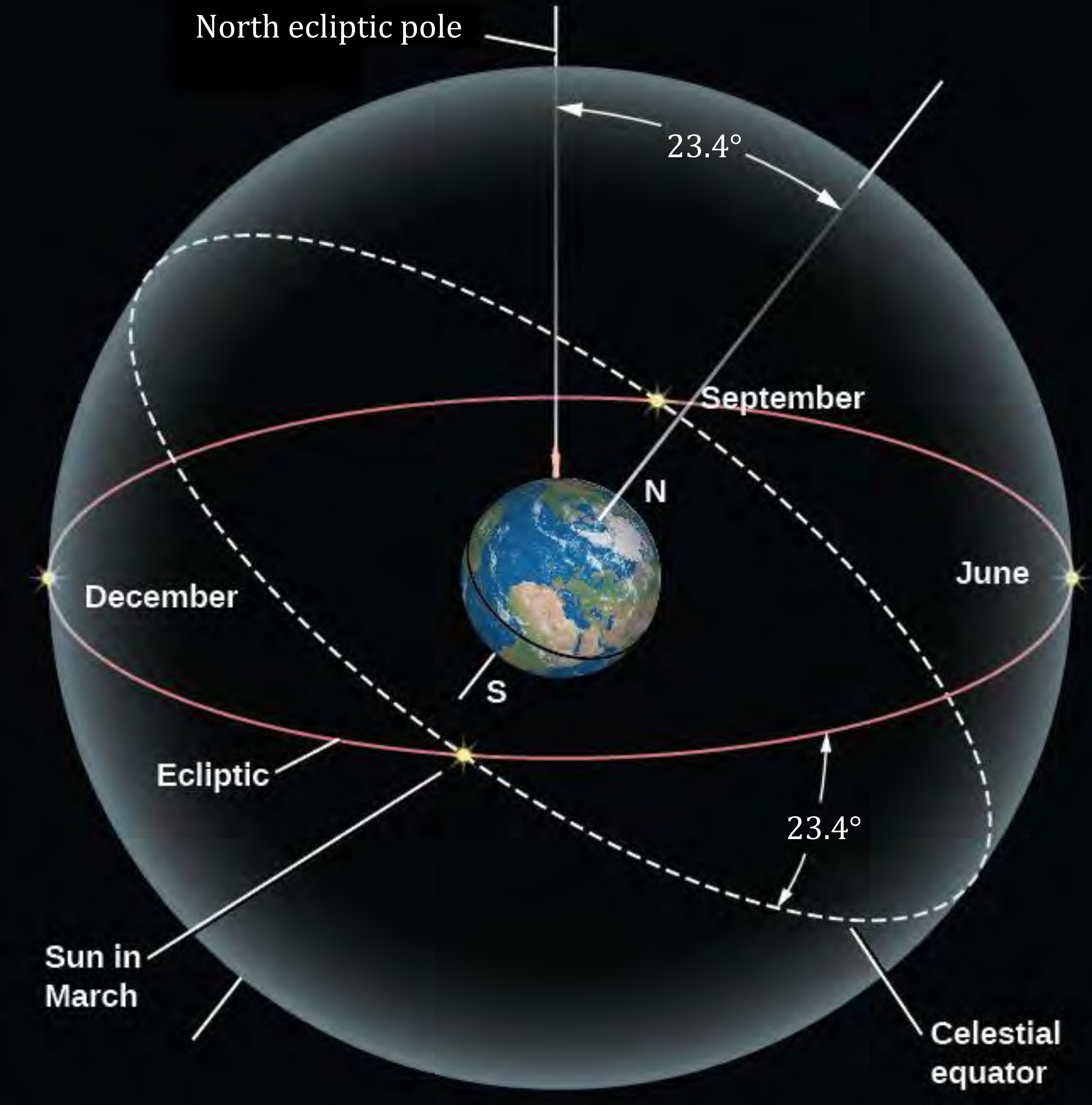


Circles on the Celestial Sphere
Credits: OpenStax Astronomy

Coordinates in the sky

- Polaris, the North Star, has declination +89°15′50.8“.
- Read: 89 degrees, 15 arcminutes, and 50.8 arcseconds.
- An arcminute (′) is 1/60 of a degree.
- An arcsecond (“) is 1/60 of an arcminute or 1/3600 of a degree.
- Note that this is very close to + 90°, the declination of the north celestial pole.





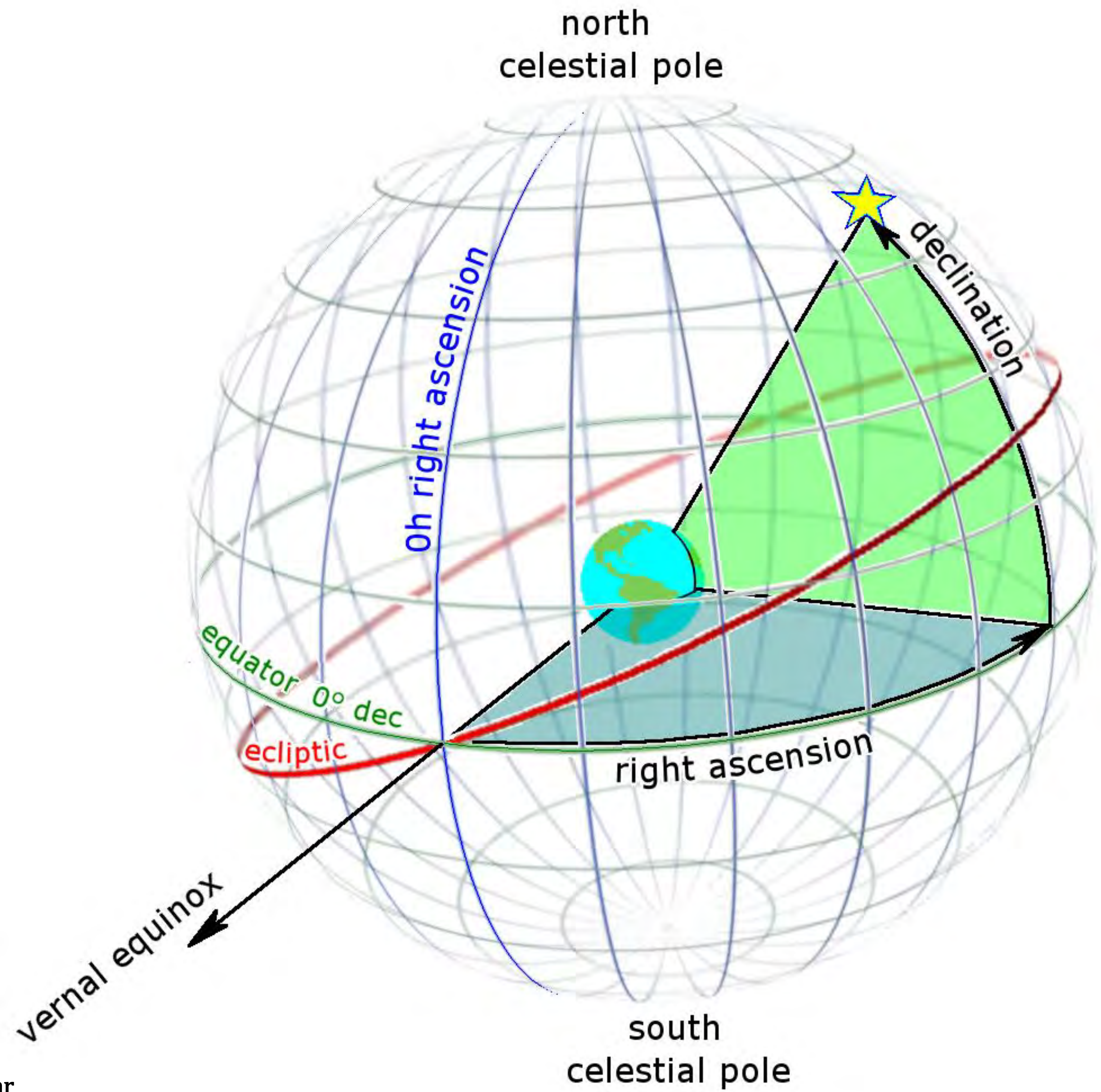
The Celestial Tilt
Credits: Modification of illustration from OpenStax Astronomy

- The plane of Earth's rotation around the Sun is the ecliptic.
- The two intersections of the ecliptic and the celestial equator are called equinoxes.
- The Sun is at the equinoxes around March 20 (the March equinox) and September 23 (the September equinox).

Coordinates in the sky

- Right ascension (RA) is like longitude: the angle east or west relative to the March equinox (instead of the prime meridian).
- RA is usually measured in units of time instead of angles.
- This is because the Earth completes one full rotation from west to east in one day.
- So 360° = 1 day = 24 hours.
- 360/24 = 15, so 1 hour = 15°.

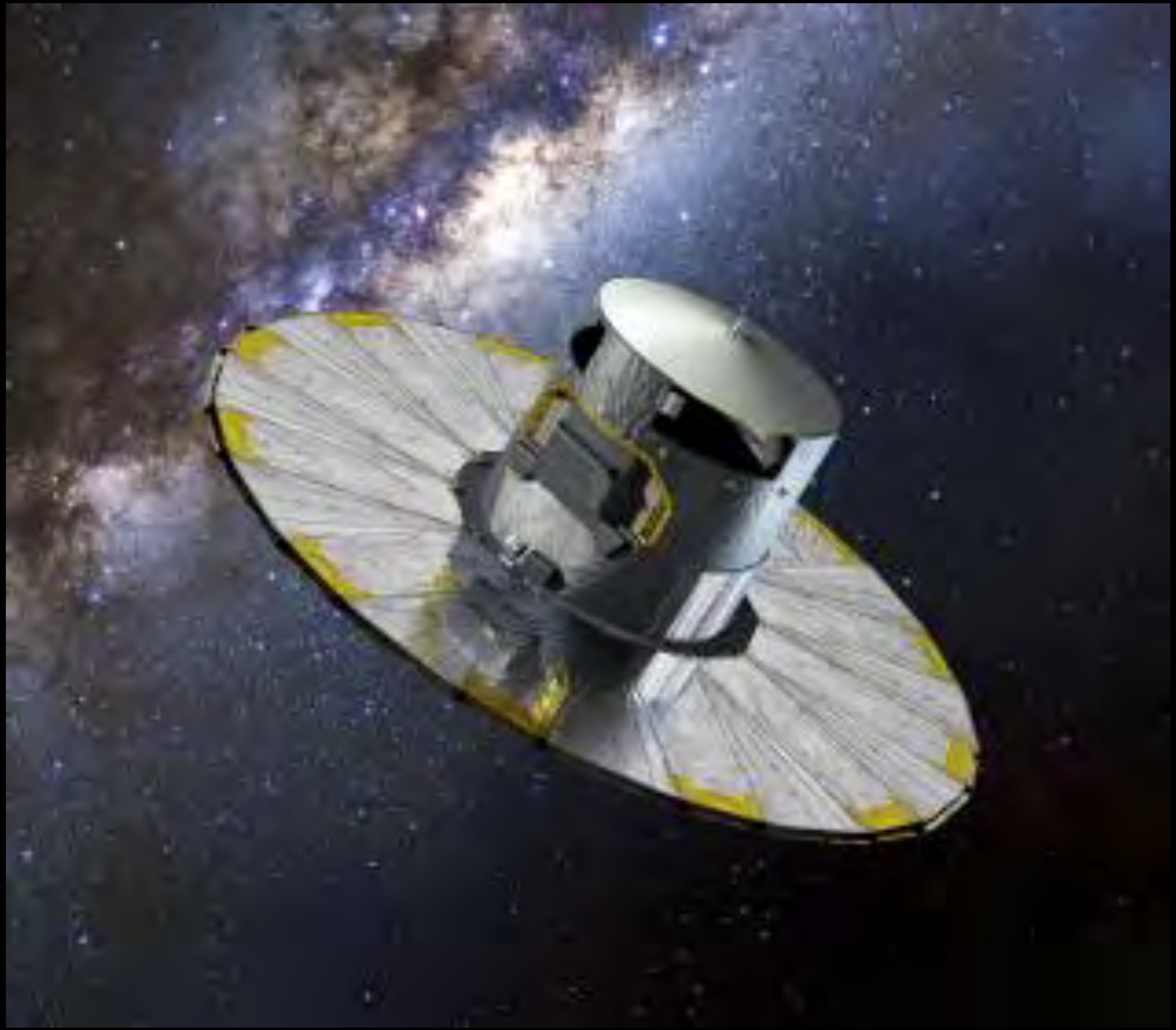
Coordinates on the Night Sky
Credits: Tfr000 (Wikipedia)



Declination and Right Ascension of a Star
Credits: Tfr000 (Wikipedia)

Coordinates in the sky

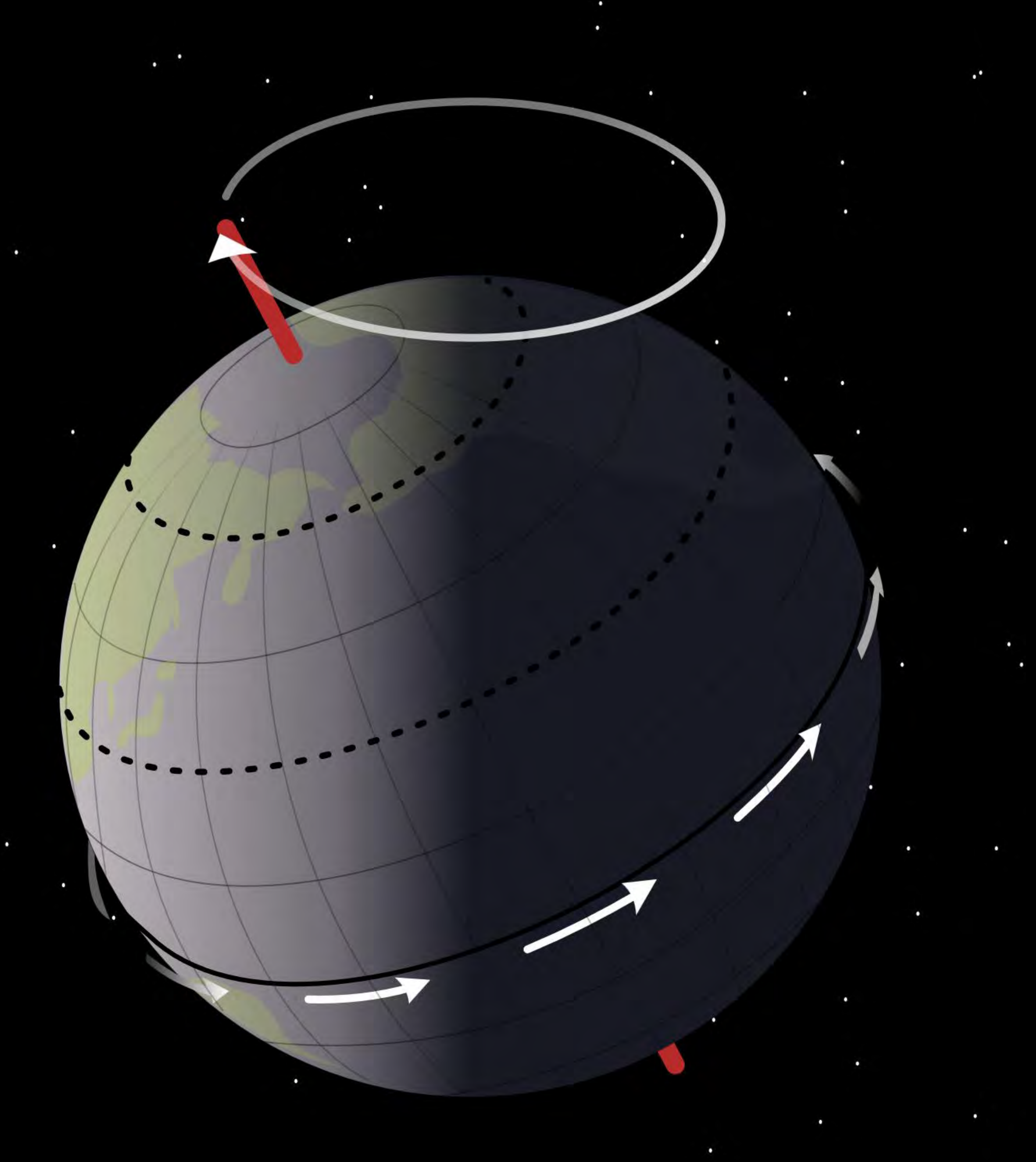
- To find the coordinates of a particular star, astronomers use tools such as star catalogs.
- Currently (until 2025), the Gaia space telescope is creating a catalog of billions of stars.
- The coordinates can also be found on websites like Wikipedia and Wolfram Alpha, or apps like Stellarium.



The Gaia Space Observatory
Credits: ESA–D. Ducros, 2013

Coordinates in the sky

- Declination and right ascension define the equatorial coordinate system.
- It seems like a simple system, but there's a complication!
- Recall that the Earth's axis experiences axial precession.
- This means the position of the north celestial pole in the sky, relative to the background stars, changes with time.
- It takes the Earth's axis around 25,700 years to complete a full circle.



Precession of Earth’s Rotational Axis
Credits: NASA, Mysid (Wikipedia)

Coordinates in the sky

- Due to this precession, the coordinates of the stars change with time.
- For example, right now Polaris is near the north celestial pole, declination +90°. But over thousands of years this will change.
- In ~11,700 years, the star Vega will be closer to declination +90°.

Precession: Spinning Top vs. Earth
Credits: OpenStax Astronomy

Coordinates in the sky

- Since the coordinates of each star depend on when they were measured, we must choose a specific time with respect to which all the coordinates will be measured.
- This is called the standard epoch.
- Currently, we use the standard epoch J2000.0, which means the coordinates are measured relative to January 1, 2000.

Demonstration

- I will show how to see declination and right ascension in the sky and find the coordinates of stars and other objects with Stellarium.
- It can be downloaded for free at the following URL:

https://stellarium.org/

Foucault's pendulum

- In 1851, physicist Jean Foucault suspended a 67-meter, 28-kg pendulum from the dome of the Panthéon in Paris.
- It had a special pivot that allowed it to swing in any direction.
- This is different from normal pendulums (like in a grandfather clock), which can only swing in one direction.
- As the pendulum was swinging, its direction of motion gradually rotated.

Foucault's pendulum

- The motion of the pendulum itself was not changing. Instead, the Earth was rotating under the pendulum!
- Therefore, Foucault's pendulum provided direct evidence that the Earth is rotating around its axis.
- At the north pole, the pendulum will complete 1 rotation clockwise (as viewed from above) every 24 hours, because the Earth is rotating around the axis of the pendulum.
- At the equator, the pendulum will not rotate at all, because the Earth rotates perpendicular to the pendulum.
- In Paris, at latitude $48°51'$ N, a full rotation takes ~ 32 hours.

Video

- This time lapse video shows a Foucault pendulum at the Orange Coast College Planetarium in California.
- At this latitude (33.7° N), the pendulum completed one full rotation every 43 hours.
- You can also see this experiment in person in many science centers, museums, and planetariums.
- The video can be found at this URL:

https://youtu.be/xmqjokCwNQs

Class demonstration

- I will demonstrate why the rotation period of Foucault’s pendulum depends on the latitude.

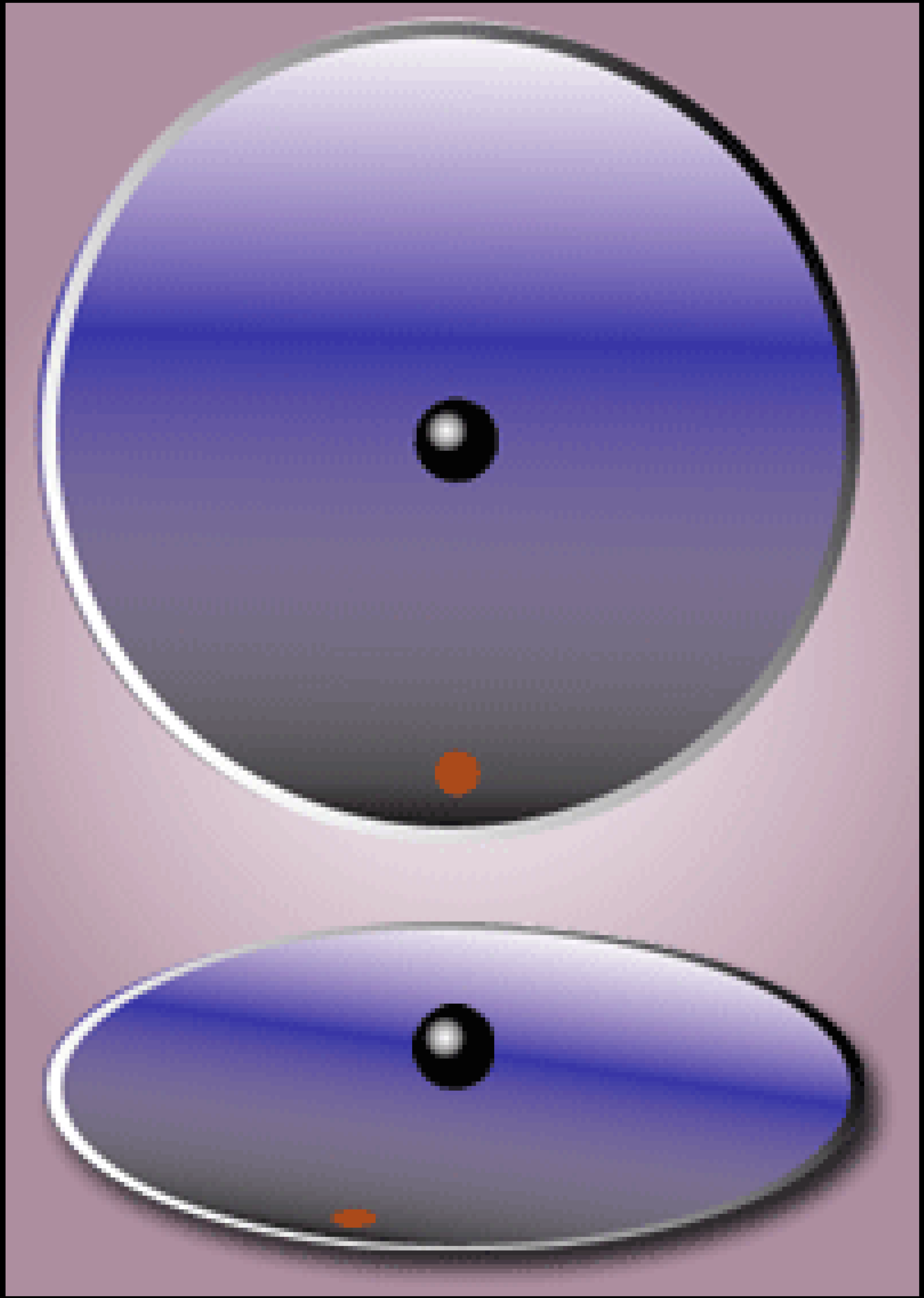
The Coriolis effect

- Another way we can detect the Earth's rotation around its axis is with the Coriolis effect.
- Remember Newton's first law: an object will keep moving at a constant speed in a straight line unless acted on by a force.
- However, this law only works in an inertial frame, which doesn't undergo any acceleration or rotation.
- Since the Earth is rotating, it's not an inertial frame (although it's close enough for most purposes).

The Coriolis effect

- When you throw a ball in an inertial frame, it will move in a straight line.
- But in a rotating (non-inertial) frame, its path will curve, even though no force is acting on it.
- We can interpret that as a "fictitious force" acting on the object. There is no actual force, but it looks like there is one.

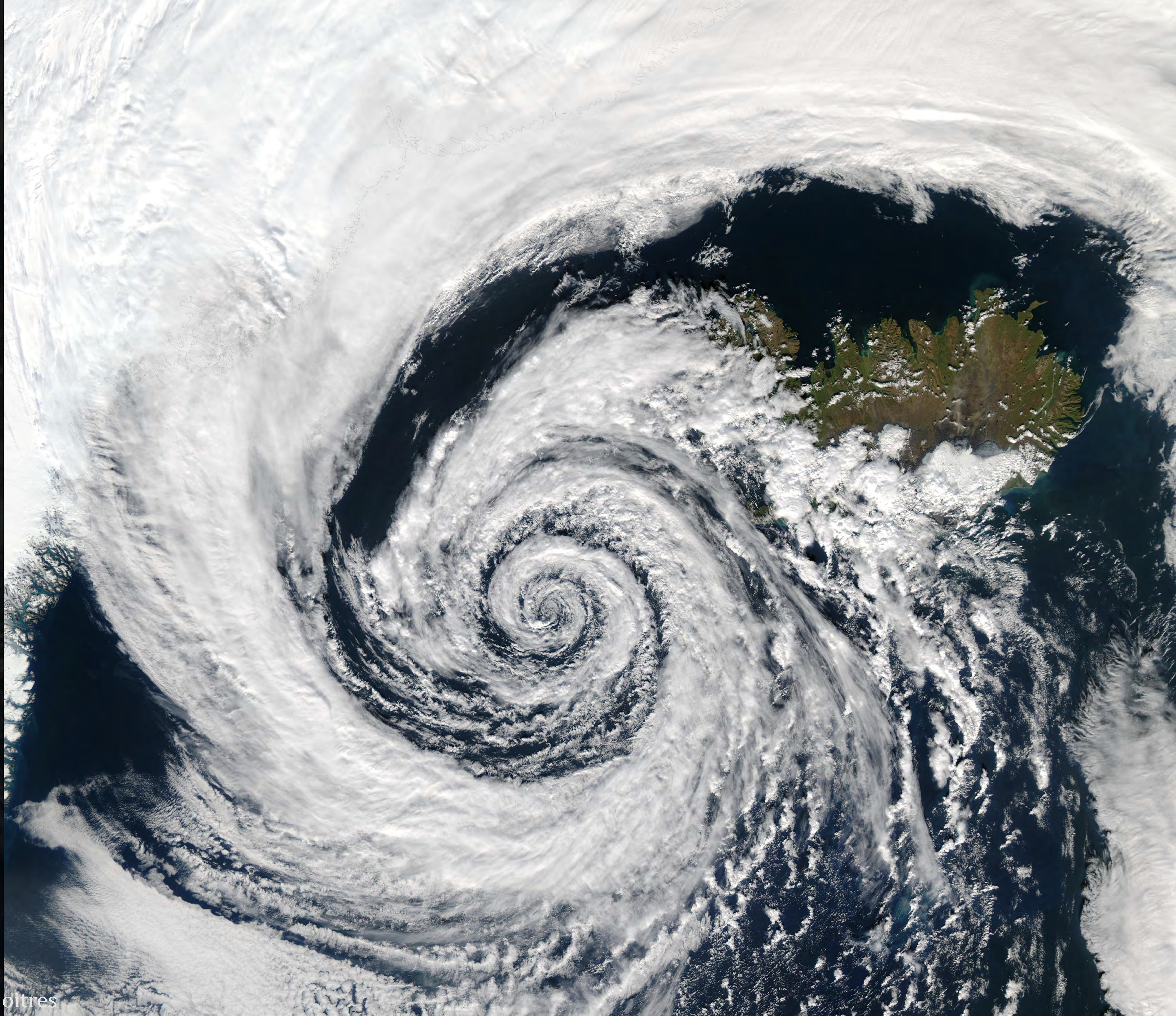
- Here we can see the Coriolis effect in action.
- On the top: view of a rotating disk from an inertial frame.
- On the bottom: view from the non-inertial frame of the disk itself.
- This animation can be found at this URL: https://commons.wikimedia.org/wiki/File:Corioliskraftanimation.gif



Demonstration of the Coriolis Force

Credits: Hubi (Wikipedia)

- The Coriolis effect causes low-pressure systems on Earth to swirl.
- Air from a high-pressure system moves in, and brings clouds with it.
- In the northern hemisphere, the wind spins counter-clockwise due to the Coriolis effect.
- In the southern hemisphere, it will spin clockwise.



A Spinning Low-Pressure System
Credits: NASA/GSFC, MODIS Rapid Response Team, Jacques Descloitres

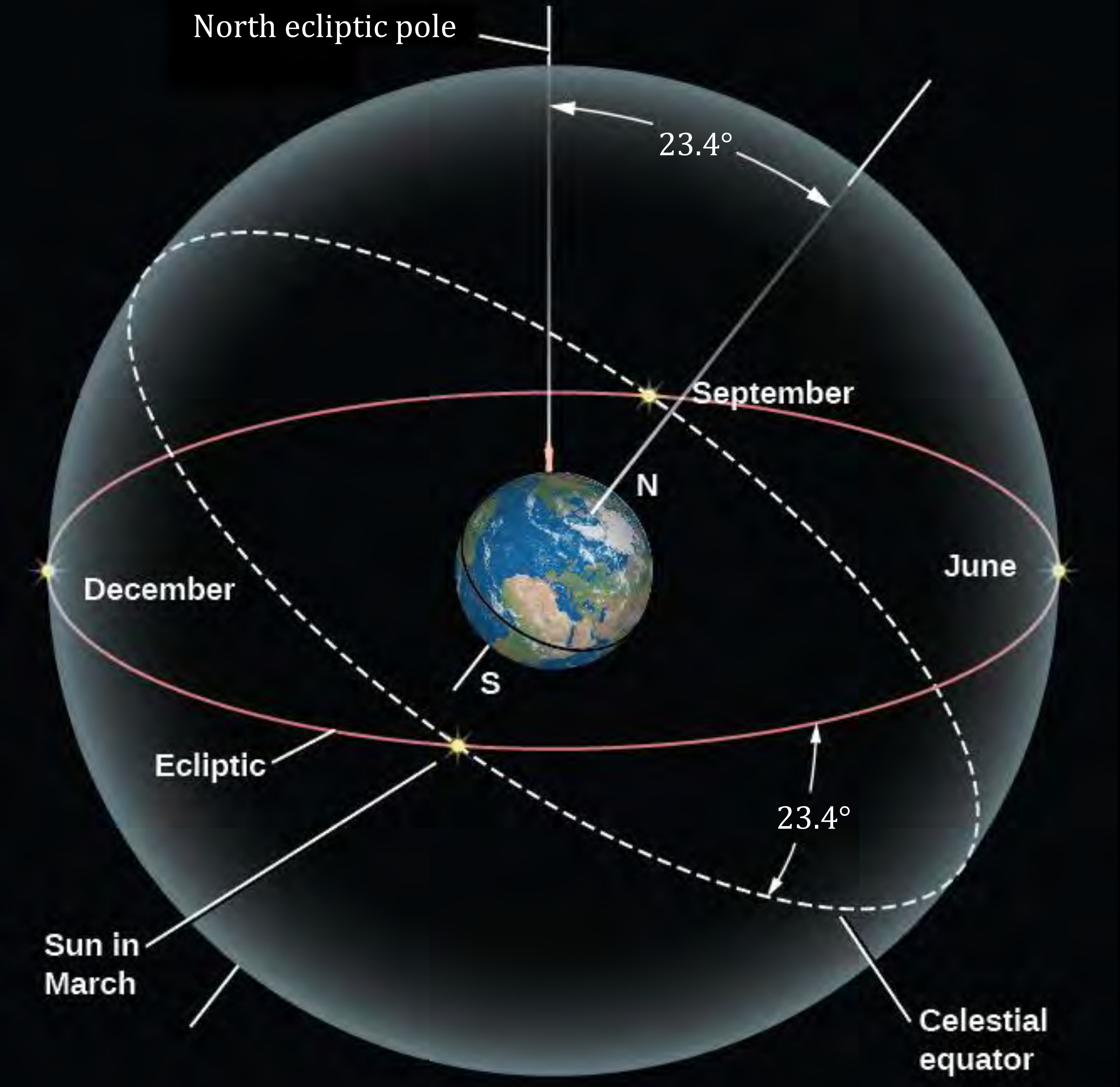
Video

- This video demonstrates the Coriolis effect using a spinning seesaw.
- It can be found at this URL:

https://youtu.be/6L5UD240mCQ

The seasons

- What causes the seasons on Earth?
- Common misconception: “the Earth gets warmer when it’s closer to the Sun”.
- But this doesn’t make sense, for several reasons:
  1. The distance from the Sun only varies by ~3% throughout the year. Earth’s orbit is an ellipse, but still very close to a perfect circle.
  2. The northern and southern hemispheres have opposite seasons, even though both are the same distance from the Sun.
  3. Earth is closest to the Sun in January, which is winter in the northern hemisphere.



The Celestial Tilt
Credits: Modification of illustration from OpenStax Astronomy

- In reality, the seasons are caused by the Earth's axial tilt.
- The plane of Earth's rotation around the Sun is the ecliptic.
- The line perpendicular to the ecliptic intersects the celestial sphere at the ecliptic poles.
- The plane of Earth's rotation around its axis intersects the celestial sphere at the celestial equator.
- The two planes of rotation differ by an axial tilt of 23.4°.

The seasons

- Since the Earth’s axis is tilted, different hemispheres “lean into” the Sun at different times, and are illuminated more directly and for a longer time.
- In June, the northern hemisphere “leans into” the Sun and the southern hemisphere “leans away” from the Sun.
- In December, the opposite happens.
- In March and September, both hemispheres “lean” sideways, perpendicular to the Sun.

The Seasons in the Northern Hemisphere
Credits: Modification of illustration from OpenStax Astronomy

The Seasons
Credits: Tau‘olunga (Wikipedia)

The seasons

- Two consequences of axial tilt are responsible for the seasons.
- First, when a hemisphere “leans into” the Sun, light hits it at a more direct angle.
- This means the same amount of light hits a smaller area of the ground.
- In other words, there is more light per unit area, so the ground heats up more.

The Sun’s Rays in Summer vs. Winter
Credits: OpenStax Astronomy

Class demonstration

- We will demonstrate this this effect by shining a flashlight on the wall at different angles.
- When the flashlight shines directly on the wall, all the light will be centered in one spot and will be the most intense.
- When it shines on the wall from an angle, the light will spread out over a large area and will be less intense.

The seasons

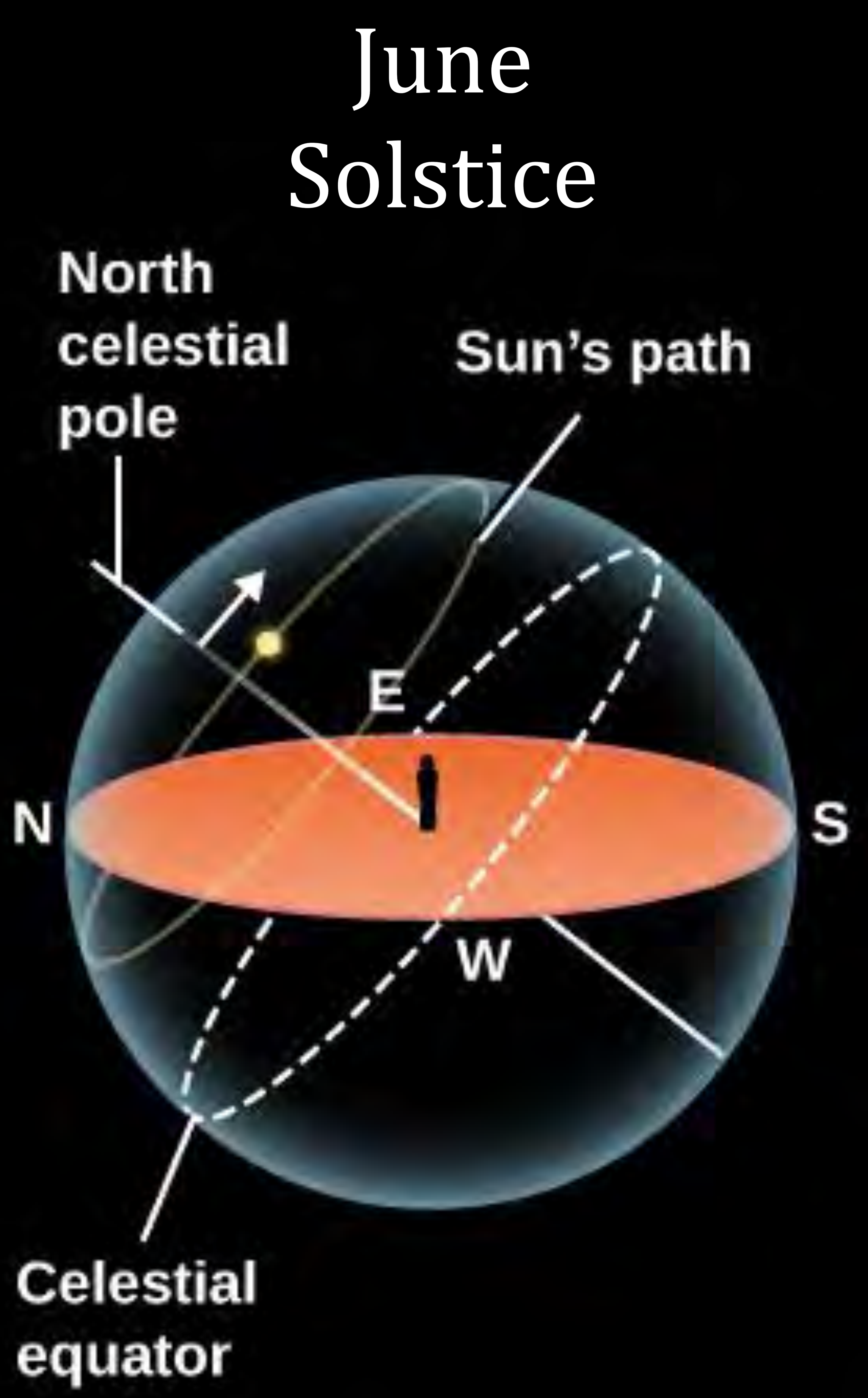
- The second consequence of axial tilt that is responsible for the seasons is how much time the Sun spends above the horizon.
- The days are longer in the summer than in the winter.
- This means the Sun shines for longer and we get more heat per day in the summer.

The seasons

- A solstice is a time when the Sun is the farthest away north or south from the celestial equator.
- There are two solstices, around June 21 and December 21.
- During the June solstice, the Sun is farthest north, so the day is the longest as seen from the northern hemisphere.
- The opposite happens during the December solstice.

The seasons

- An equinox is the time when the Sun is exactly at the celestial equator.
- There are two equinoxes, around March 20 and September 23.
- During both equinoxes, the Sun spends an equal amount of time above and below the horizon in both hemispheres.
- Therefore, during the equinoxes, the day and night have the same length everywhere on the planet.



The Sun's Path in the Sky for Different Seasons
Credits: Modification of illustration from OpenStax Astronomy

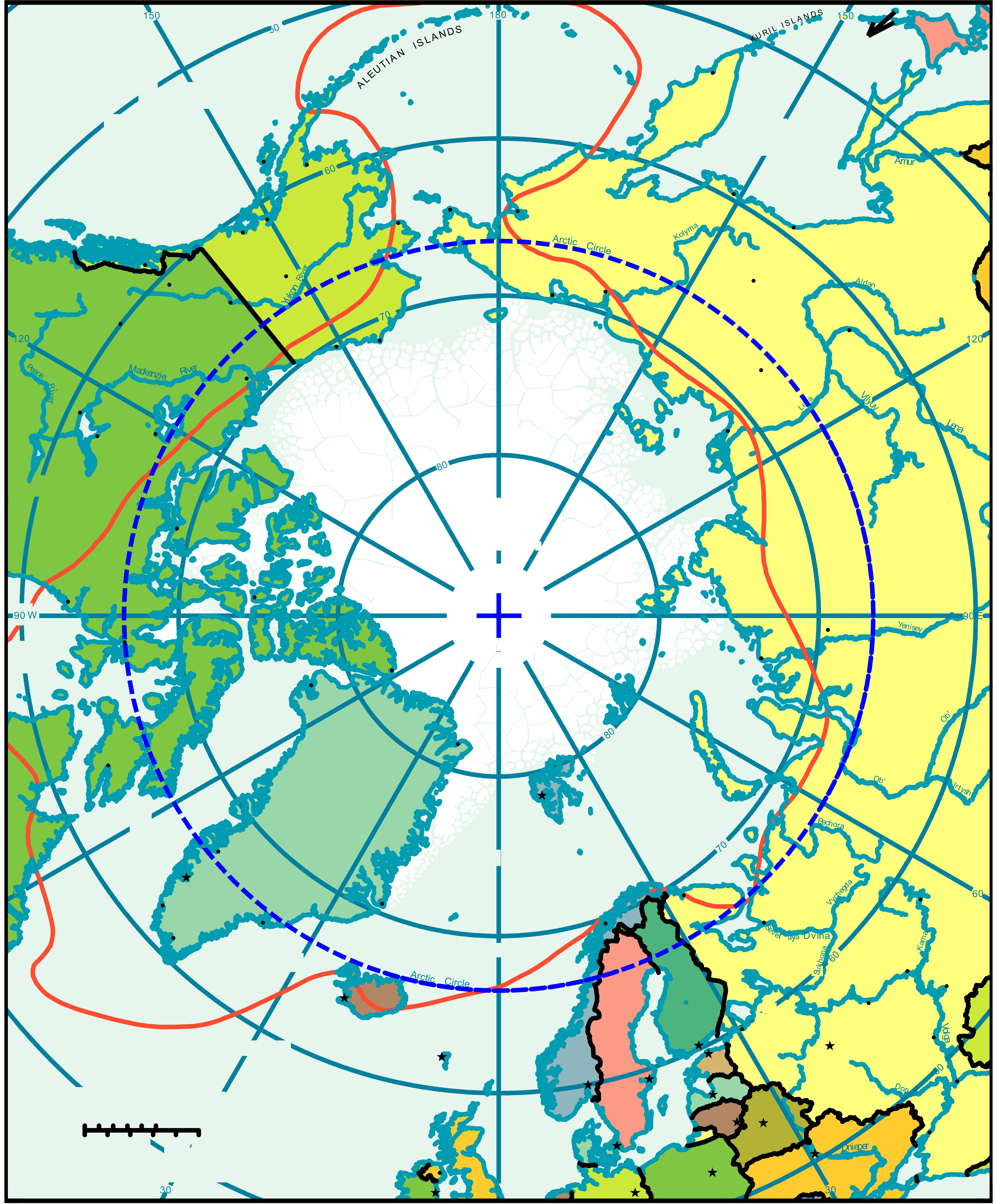
Circles of latitude

- During the June solstice, the Sun is 23.4° north of the equator.
- Therefore, it passes exactly through the zenith in places that are at latitude 23.4° N.
- This latitude is called the Tropic of Cancer (or the Northern Tropic).
  - When it was named, a few thousand years ago, the Sun was at the constellation Cancer at the June solstice.
  - However, due to axial precession, the Sun is now in Taurus at that time.
- North of the Northern Tropic, the Sun can never be at the zenith.

Circles of latitude

- The Arctic Circle is the circle of latitude 66.6° N.
- Anything above the arctic circle is within 23.4° of the north pole.
- That’s because $90° - 23.4° = 66.6°$.
- On the Arctic Circle, on the June solstice, the Sun shines for a full 24-hour period. This phenomenon is called the “midnight sun”.
- The further north you go, the longer the midnight sun becomes.
- At the North Pole, latitude 90° N, the Sun shines for 6 full months.

Earth During the June Solstice
Credits: OpenStax Astronomy



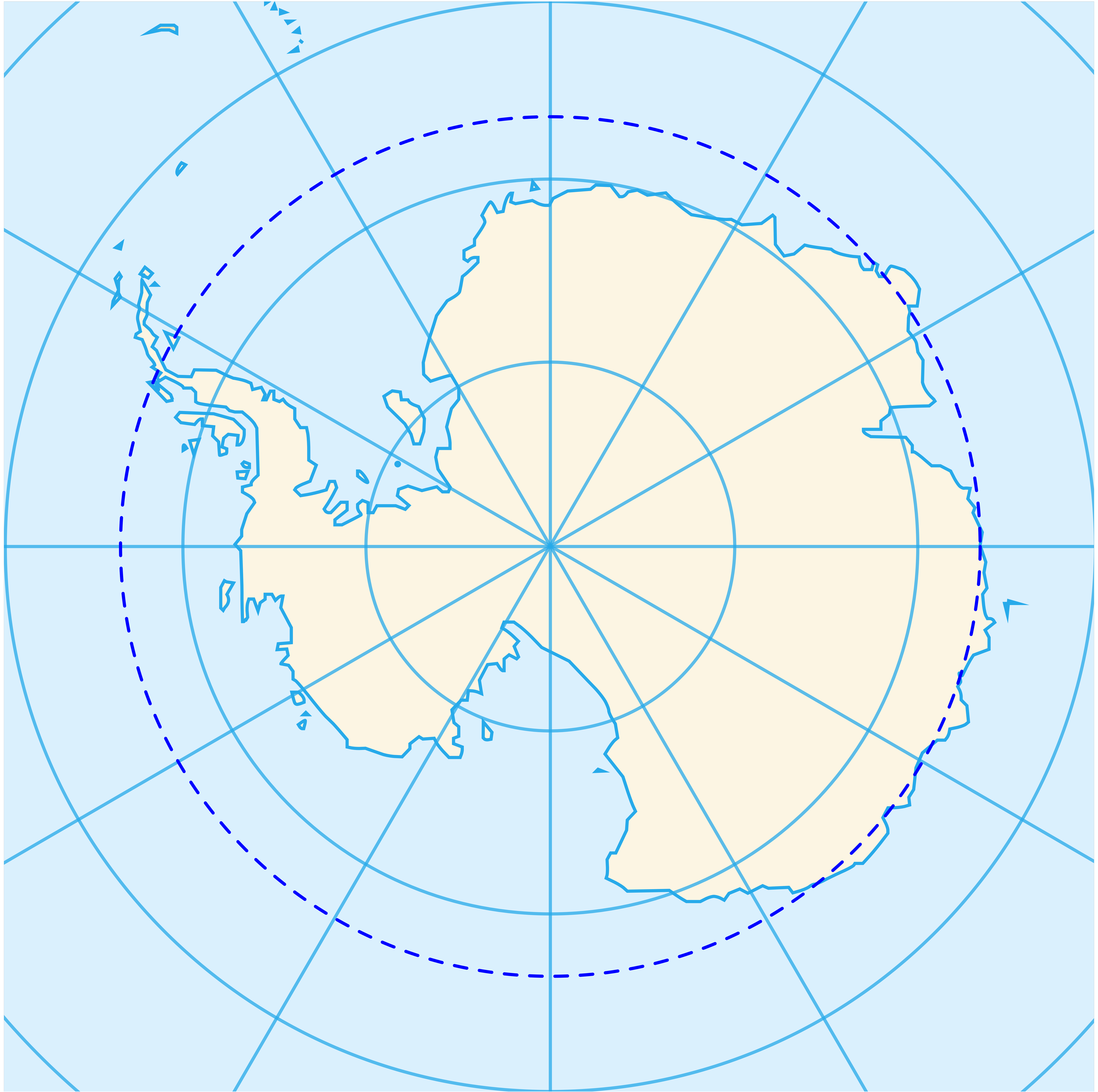
The Arctic

Credits: CIA World Fact Book

Circles of latitude

- These circles of latitude have southern counterparts.
- The Tropic of Capricorn (or the Southern Tropic) is at latitude 23.4° S.
    - When it was named, the Sun was at the constellation Capricornus at the December solstice. Due to axial precession, the Sun is now in Sagittarius at that time.
- The Antarctic Circle is at latitude 66.6° S.

Earth During the December Solstice
Credits: OpenStax Astronomy



The Antarctic
Credits: Thesevenseas (Wikipedia)

World Map Indicating Tropics and Subtropics
Credits: KVDP (Wikipedia)

The Tropics and Polar Circles
Credits: Cmglee (Wikipedia), NASA

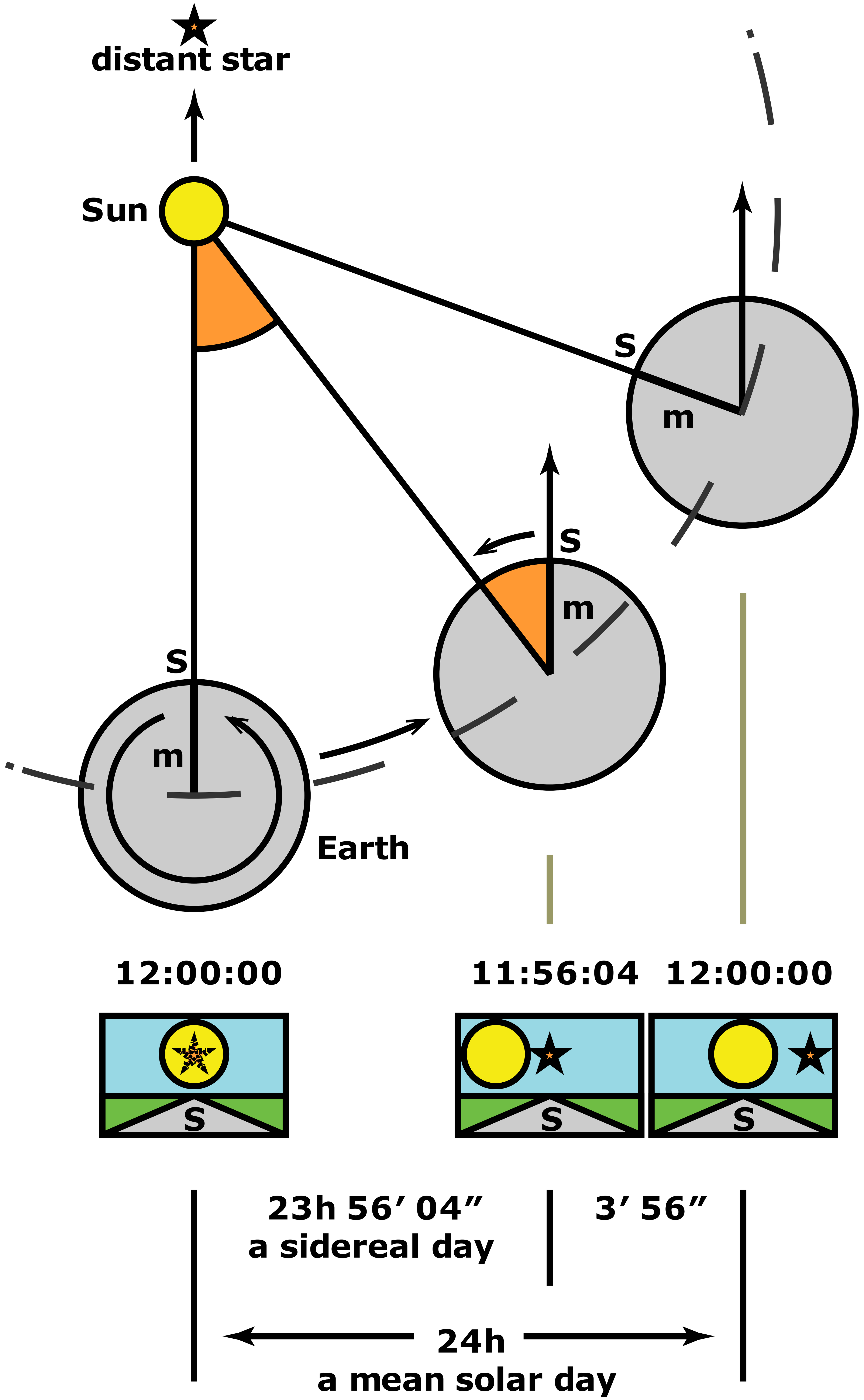
The calendar

- There are two ways to define the length of a day.
- A solar day (or synodic day) is the rotation period with respect to the Sun. It is 24 hours long.
- This is what we normally call a “day” in colloquial use.
- A sidereal day (sy-DEER-ee-al) is the rotation period with respect to the fixed stars. It is 23 hours and 56 minutes long.
- Sidereal days are more convenient to use in astronomy, because each star rises at the same sidereal time every day.

The calendar

- The reason a solar day is 4 minutes longer is that it is also influenced by the rotation of Earth in its orbit around the Sun.
- The Earth moves in its orbit relative to the Sun, but it doesn’t move relative to the fixed stars (because they’re so far away).
- One full rotation of the Earth around its axis is 23 hours and 56 minutes. But then an additional 4 minutes are required until the Sun is at the same position in the sky.
- These 4 minutes are equal to 1/365 or ~1° of a full turn.
  - 24 hours $\times$ 60/365 $\approx$ 4 minutes.

- At 12:00 solar time on day 1, both the Sun and a fixed star are at the zenith.
- At 11:56 on day 2, the fixed star is back at the zenith. One sidereal day has passed.
- 4 minutes later, at 12:00 on day 2, the Sun is back at the zenith. One solar day has passed.



Sidereal Time vs. Solar Time
Credits: Xaonon (Wikipedia)

The calendar

- Apparent solar time is the time given by the actual position of the Sun in the sky, as indicated by a sundial.
- But the length of an apparent solar day varies throughout the year, since Earth's orbit is an ellipse and its axis is tilted.
- Mean solar time is based on the average length of the solar day over a year.
- A mean solar day is 24 hours long.

The calendar

- A year is defined as the orbital period of the Earth.
- In astronomy, we define a Julian year to be exactly 365.25 days of 24 hours each.
- A year with an extra ¼ day would be confusing to use in our daily lives. So instead we define a year to be 365 days, but add 1 extra day (February 29) on leap years.
- A year is a leap year if it's divisible by 4, but not by 100, unless it's divisible by 400.
    - So 1900 was not a leap year, but 2000 was.
    - The next leap year will be 2024.

Phases of the Moon

- The Moon's sidereal orbital period (with respect to the fixed stars) is ~27.3 days.
- The synodic orbital period (with respect to the Sun) is ~29.5 days, known as a lunar month.
- The synodic period is longer because the Earth-Moon system moves relative to the Sun while the Moon orbits Earth.

Phases of the Moon

- Interestingly, 1 solar day on the Moon is equal to 1 lunar month.
- In other words, the Moon rotates around its axis, going through one day-night cycle, in the same amount of time it takes to orbit Earth.
- This is called synchronous rotation or 1:1 spin-orbit resonance.
- It means we always see the same side of the Moon.
- The side we don't see is sometimes mistakenly called the "dark side" of the Moon, but in fact it's not dark! It's illuminated when it faces the Sun, just like the rest of the Moon.

Phases of the Moon

- During a lunar month, we see different parts of the Moon illuminated.
- This is because the Moon rotates around the Earth, so the direction of the Moon facing the Sun changes.
- During a new moon, the Moon is between the Earth and the Sun, so it appears dark. Only the back side of the Moon is illuminated.
- During a full moon, the Moon is on the side opposite the Sun, so it appears fully illuminated.

Phases of the Moon. The outer image shows how the Moon appears to us in the sky. Distances not to scale.
Credits: OpenStax Astronomy

Class demonstration

- We will demonstrate the phases of the Moon using a flashlight, a globe, and a ball.

The tides

- Earth exerts a gravitational force on the Moon to keep it in orbit.
- According to Newton’s 3rd law, the Moon exerts an equal and opposite gravitational force on Earth.
- Earth is larger, so different parts of it are at different directions and distances from the Moon.
- Therefore, different parts experience forces in different directions and magnitudes.

Gravitational Pull of the Moon on Earth
Credits: OpenStax Astronomy

The tides

- This causes the Earth to stretch into an oblate spheroid (like an American football).
- If the Earth was made entirely of water, its shape would differ from a sphere by ~1 meter.
- However, since most of the Earth is more rigid, the distortion is only ~20 cm.
- Earth has tidal bulges both on the side facing the Moon and the side opposite the Moon.

Tidal Bulges
Credits: OpenStax Astronomy

The tides

- The tidal bulges are not caused by the Moon "lifting" the water away from Earth.
- If that was the case, there would only be one bulge, not two.
- The Sun also influences the tides, but less than the Moon.
- At new moon or full moon, when the Sun and the Moon are lined up, the tidal forces reinforce each other (spring tide).
- When the Sun and the Moon are in perpendicular directions, they partially cancel each other (neap tide).

Tidal Bulges
Credits: OpenStax Astronomy

The tides

- In reality, tides are a bit more complicated than this, because the Earth is not made entirely of water.
- Factors that complicate the tides include:
  - Land masses stopping the flow of water.
  - Friction in the oceans, and between oceans and the ocean floor.
  - The rotation of Earth.
  - Wind.
  - Variable ocean depths.

The tides

- The tides also have the side effect of transferring angular momentum from Earth to the Moon.
- This means Earth's rotation around its axis slows down a bit, and the Moon's orbital distance increases a bit.
- The slowing of Earth's rotation means the days get longer by ~17 microseconds (millionths of a second) every year.
- The distance to the Moon increases by ~38 mm every year.

The tides

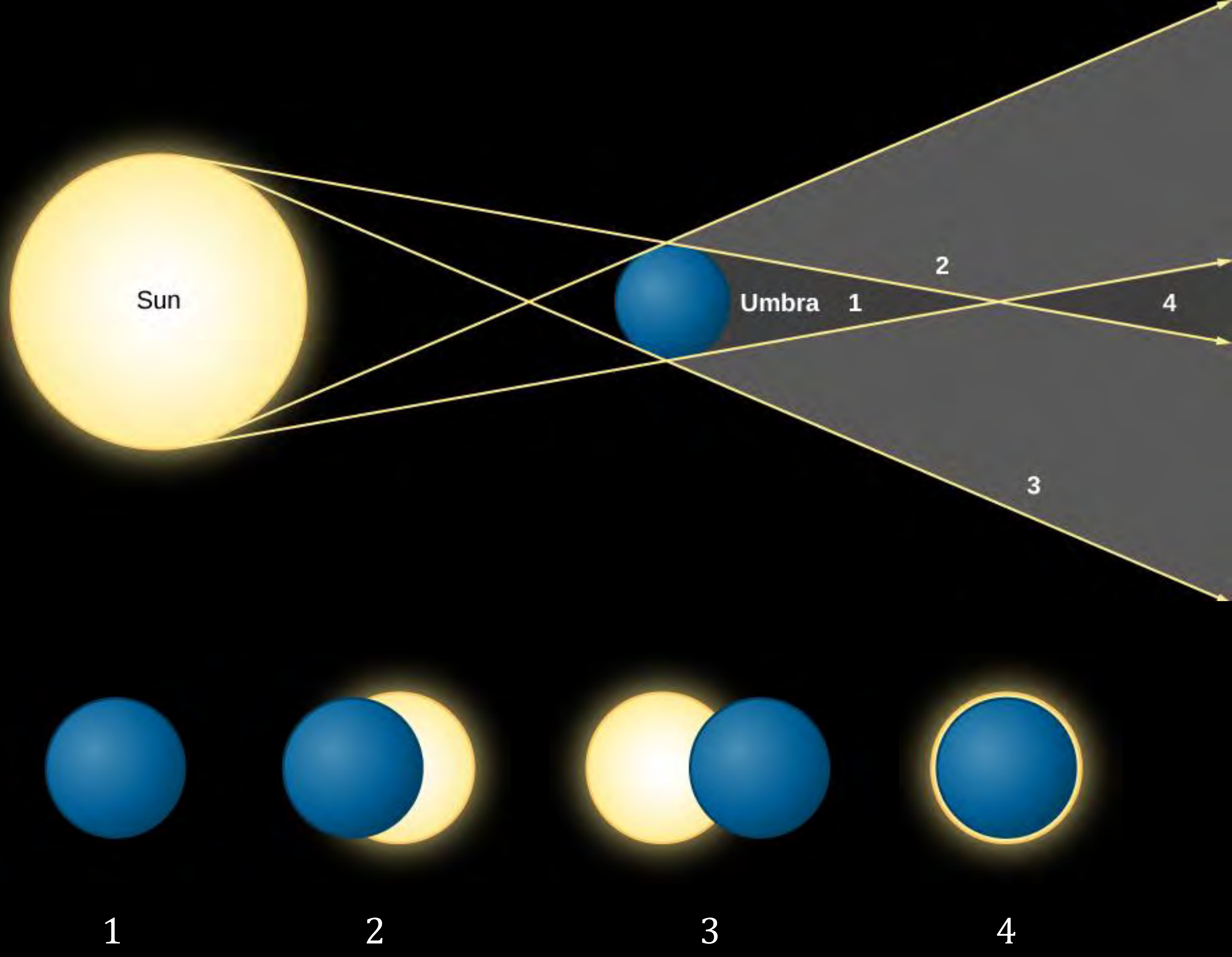
- Tides are also responsible for the Moon’s synchronous rotation due to tidal locking.
- In the past, tidal effects caused the Moon’s rotation around its axis to slow down over time.
- Once the rotation period matched the orbital period, these effects stopped.
- Hypothetically, in ~50 billion years, Earth’s rotation will slow down enough to tidally lock it to the Moon as well. Then we will only see the Moon from one side of the Earth.
  - This may not actually happen, since a lot can change by then.

Eclipses

- The Sun is ~400 times larger than the Moon.
- However, it's also ~400 times farther away.
- So both the Sun and the Moon have the same size as seen from Earth (angular size of ~1/2°).
- Therefore, the Moon can sometimes cover the Sun. This is called a solar eclipse.
- Any object casts a shadow by blocking the light from the Sun. During a solar eclipse, the Moon casts a shadow on Earth.
- Only people within the shadow see the eclipse.

A Total Solar Eclipse
Credits: OpenStax Astronomy

- A shadow consists of two parts.
- The umbra (AHM-bra) is the cone where the shadow is darkest.
- The penumbra is the lighter region.
- The view of the Sun and Moon from Earth when it's at each point is shown below.



Umbra and Penumbra
Credits: Modification of illustration from OpenStax Astronomy

- During a total solar eclipse, we can see the corona, the Sun's outer atmosphere.
- It is usually not visible because it's too faint.
- Be careful! Even though the Sun is covered by the Moon, it's still dangerous to look directly at the Sun during a solar eclipse.
- Only observe the Sun through eclipse glasses or other safe methods.

The Sun's Corona During a Total Solar Eclipse
Credits: OpenStax Astronomy (modification of work by Lutfar Rahman Nirjhar)

Eclipses

- During a lunar eclipse, the Moon enters the shadow of Earth.
- Unlike a solar eclipse, a lunar eclipse is visible to anyone who can see the Moon, anywhere on Earth.
- That's because the shadow is on the Moon itself.
- Therefore, lunar eclipses are observed more frequently than solar eclipses.

A Lunar Eclipse
Credits: OpenStax Astronomy

Time Lapse of a Lunar Eclipse
Credits: Thomas Knoblauch, https://en.wikipedia.org/wiki/File:2007-03-03_-_Lunar_Eclipse_small-43img.gif

Class demonstration

- We will demonstrate solar and lunar eclipses using a flashlight, a globe, and a ball.

Conclusions

- In this lecture, we learned about astronomical phenomena that affect Earth.
- Many of them affect our daily lives. Some are just cool to see!

- Reading: OpenStax Astronomy, chapter 4.
- Exercises: Practice questions will be posted on Teams.