Chap 2:
Motions of Earth and the Moon -

a. Celestial Sphere & Coordinates
b. Time, Calendar, & Navigation
c. Longterm Climate Change

Chapter 2a: The Celestial Sphere

- The English word **astronomy** originated from Greek ἀστρονομία, where ἄστρον means **astron, "star"** and -νομία means -**nomia "law"**.
- "Star arrangements" on the sky changes as geological location and time changes
    - **Constellations** - the arrangement of stars
    - **Celestial Sphere: (Alt-Az) & (RA, Dec) coordinates**
- **Diurnal motion** caused by the spin of the Earth
- **Seasons** caused by the orbit and tilt of the Earth
- **Moon phases and eclipses** caused by relative angles between the Moon and the Sun, as Aristotle realized around 350 BC
- **Fine motion of the Earth** - Precession of the Earth's spin axis
    - Causes of Ice Ages (Could it also cause the climate change?)

Time Keeping, Celestial Navigation, and Astro Observations

- **RA & Dec of an object:** predefined on sky charts
- **Calendar & Time**
  Geological location + Sky Position ⇒ Date & Time
- **Celestial navigation:**
  Time + Sky Position ⇒ Geological location
- **Astronomical Observations**
  Time + Geological location ⇒ Sky Position

Chapter 2b: Time & Calendar

- How do we keep time?
  through astronomical observations

- What do A.M. & P.M. mean?
  Latin: *ante/post meridiem (of Sol)*

- How do we make calendar?
  Originally for the purposes of agriculture and religious rituals

- How do we predict the position of objects on the sky?
  Based on date, time, geological location, and celestial coordinates

- How do we navigate through the sea?
  With astronomical observations and marine chronometer

The calendar we use today originated from this ancient city, what is it?

Roman Kingdom (753–509 BC), Roman Republic (509–27 BC), and Roman Empire (27 BC–476 AD)

The Names of Months (from Romulus[753BC, Lunar]-Julian[63BC, Solar] Calendar)

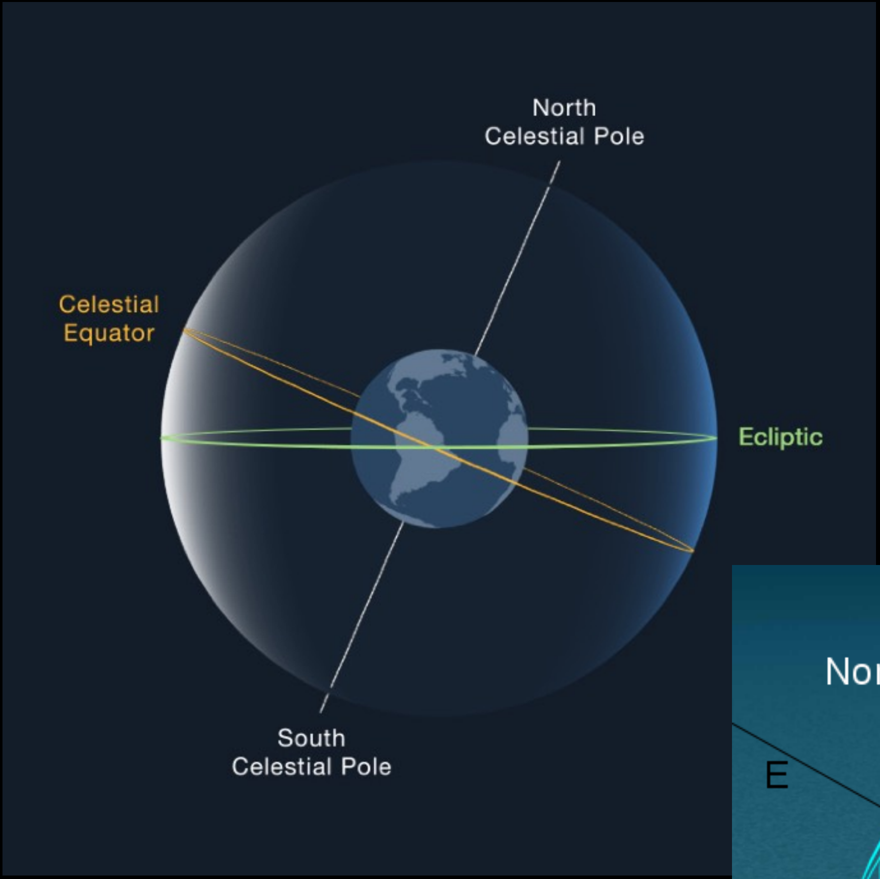
1. March - Mars, the god of war
2. April - Latin aperio “to open”
3. May - Goddess Maia
4. June - Goddess Juno
5. July - Julius Caesar, Roman Emperor (renamed in 44 BC)
6. August - Augustus, Roman Emperor (renamed in 8 BC)
7. September - Latin 7th
8. October - Latin 8th
9. November - Latin 9th
10. December - Latin 10th
11. January - Janus, the Roman god of beginnings and transition
12. February - Februa, a festival for springtime cleaning and washing

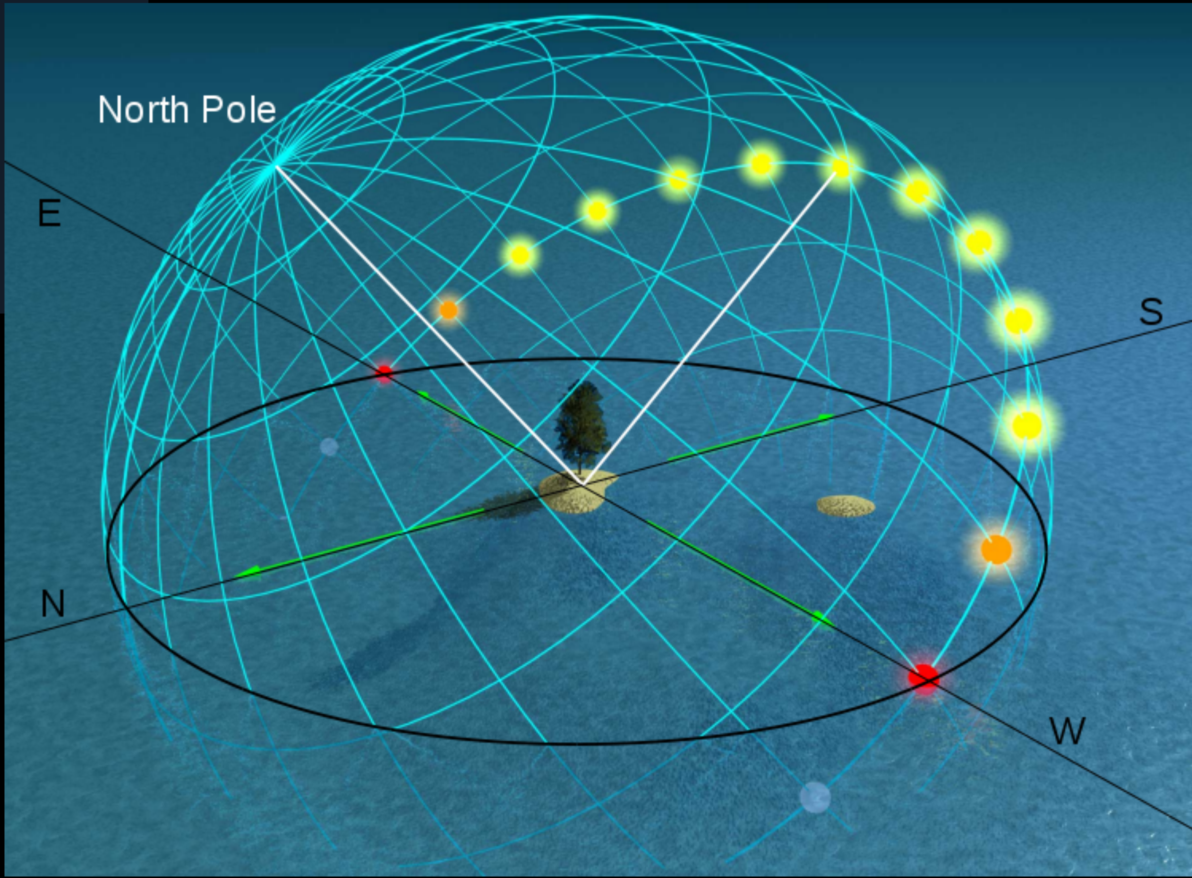
The Days of a Week (invented by Babylonians of Akkadian Empire 2300 BC, renamed by Romans)

1. Monday - in Latin *dies Lunae (Luna)*
2. Tuesday - *dies Martis (Mars)*
3. Wednesday - *dies Mercurili (Mercury)*
4. Thursday - *dies Jovis (Jupiter)*
5. Friday - *dies Veneris (Venus)*
6. Saturday - *dies Saturni (Saturn)*
7. Sunday - *dies Solis (Sol)*

Italian - *lunedi, martedi, mercoledi, giovedi, venerdi, sabato, domenica*

Angular Coordinate Systems

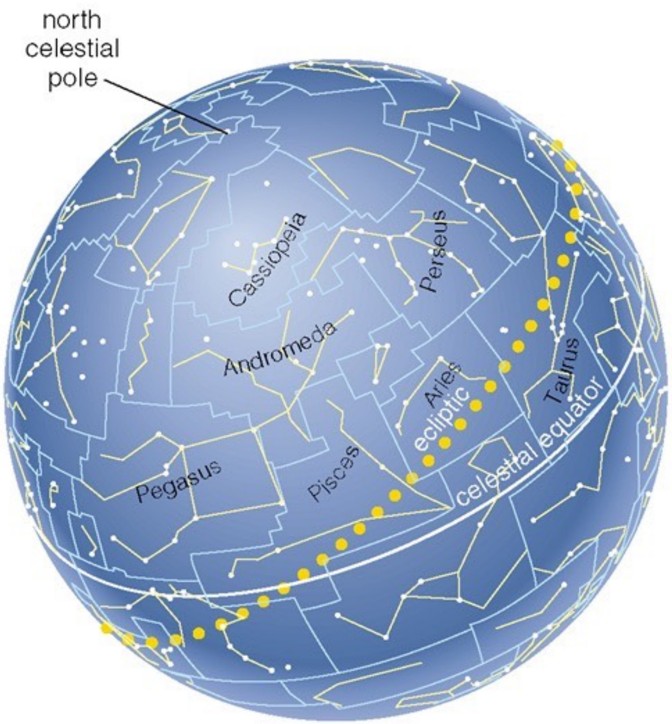




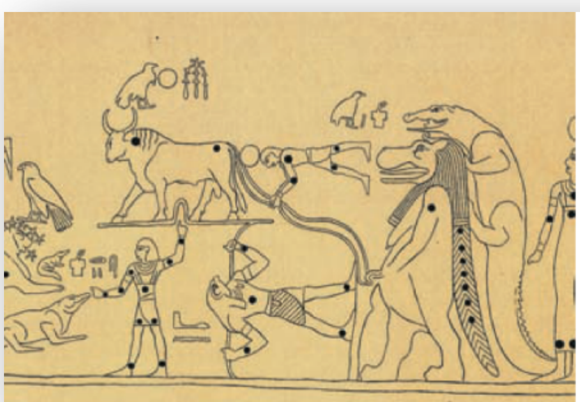
Constellations on the celestial sphere

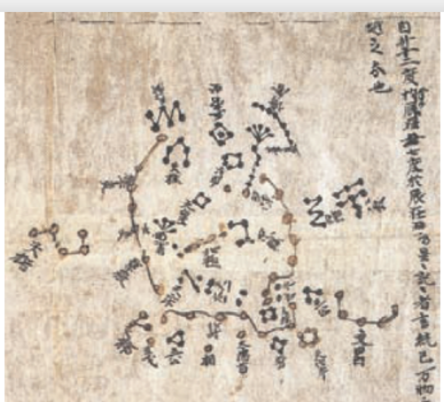

Ophiuchus
Scutum
Libra
Winter Solstice
300°
270°
240°
210°
Sagittarius
Scorpius
Corona Australis
Triangulum
Telescopiu
Lupus
Indus
Ara
Triangulum Australe
Pavo

Constellations based on Greece-Roman Mythology



- **The entire sky** is broken up into 88 regions (48 original): **constellations**
- Stars within each region create arbitrary patterns
- Resulting myths from human imagination





The division of the celestial sphere is arbitrary: e.g., Lunar Mansions (East Asia) vs. Zodiac Constellations (Europe)

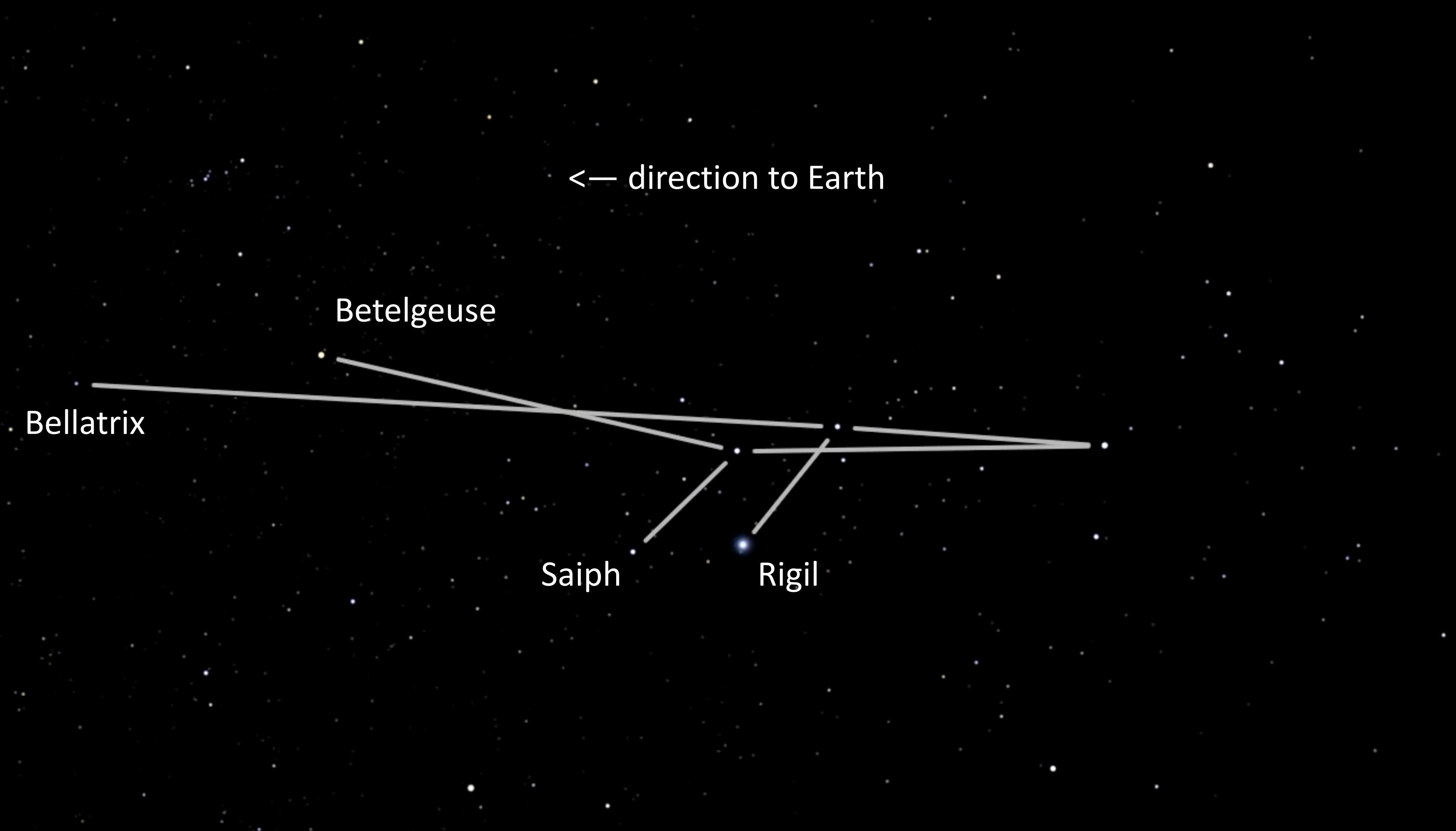
- The stars along the path of the Moon are divided into four quadrants
  - Azure Dragon of the East
  - Black Tortoise of the North
  - White Tiger of the West
  - Vermilion Bird of the South
- Each quadrant has seven lunar mansions
- These 28 lunar mansions correspond to the 12 Zodiac constellations

Stars in the Same Constellation are not at the same distances to us. And brighter stars are not necessarily closer than fainter stars

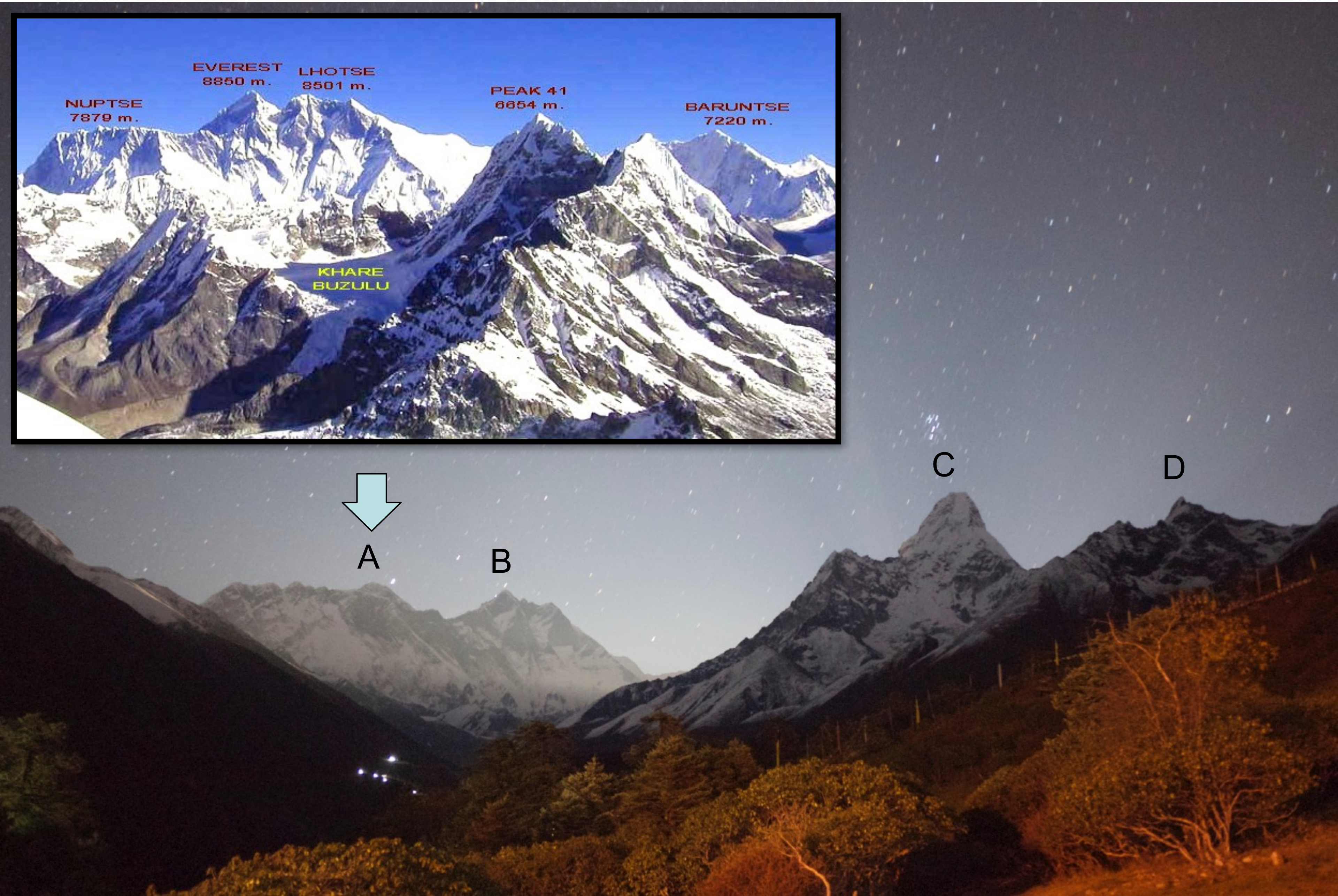
Stars in a constellation are not related. e.g., see the Orion Constellation in 3D

Stars in the Same Constellation are not at the same distances to us. And brighter stars are not necessarily closer than fainter stars

Brighter stars are not necessarily closer than fainter stars, because they could have very different luminosities



Where is Mt. Everest?



So what is a constellation?

A region of the sky with bright stars forming a **projected pattern** that evokes *imaginations*

These projected patterns change over time because stars move (proper motion)

These projected patterns are arbitrary (meaningless)

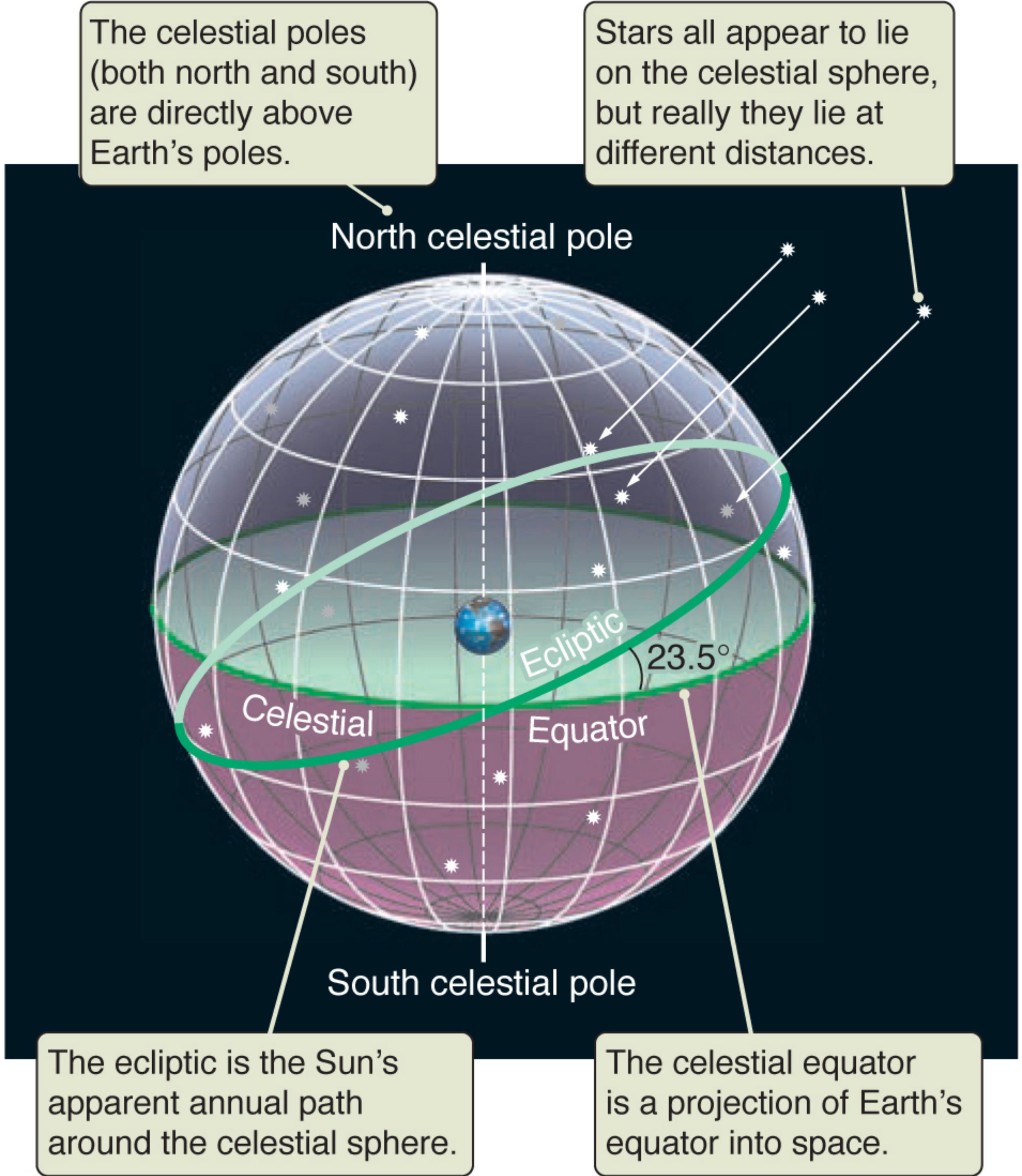
Angular Coordinates on the Celestial Sphere

Right Ascension and Declination (RA, Dec) are **defined** using an intuitive coordinate system

They do not change over decades for objects outside off the Solar system

Stars appear fixed on the imaginary celestial sphere,

while the Sun, the Moon, and other Solar system objects move across the celestial sphere

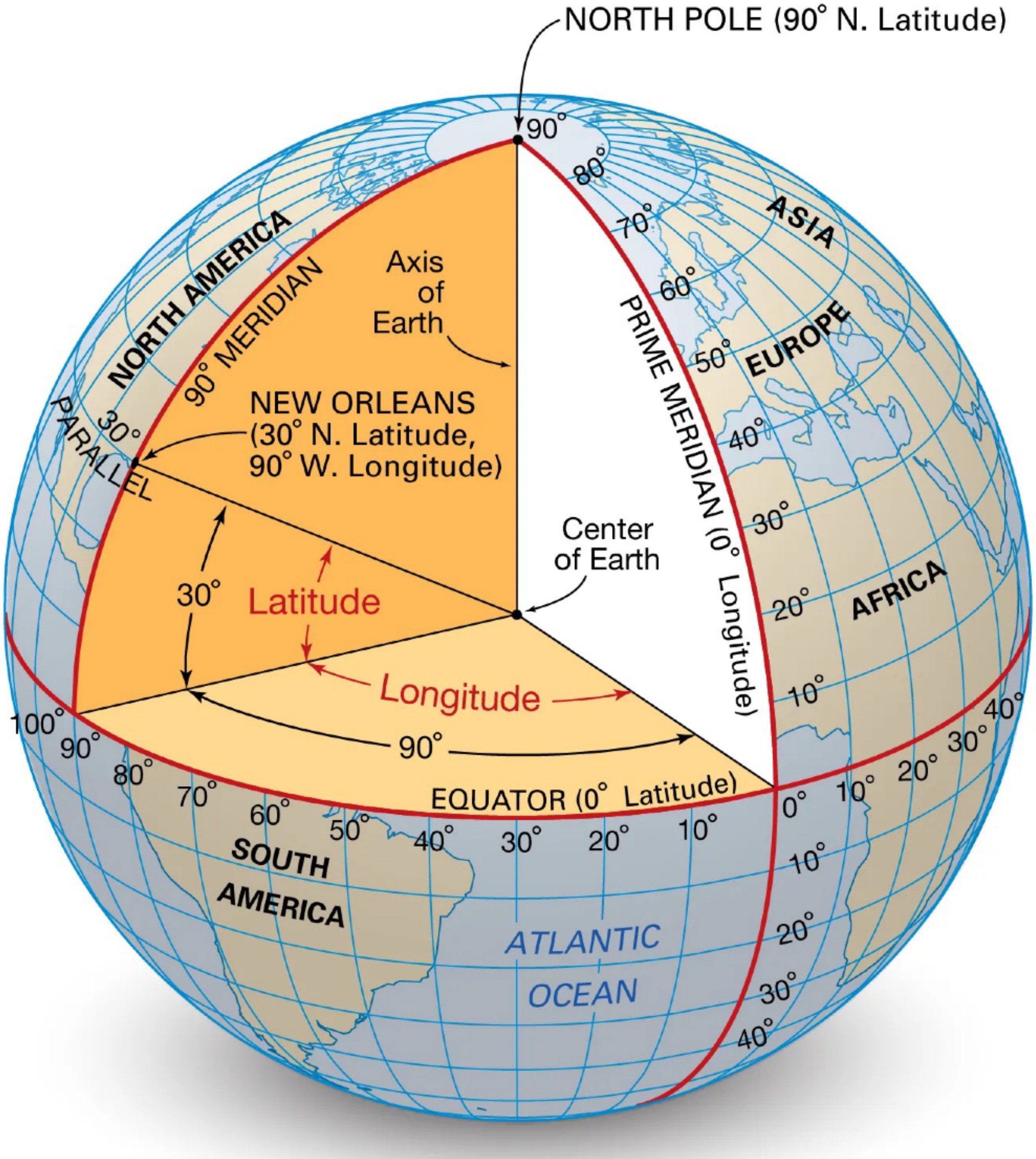


RA & Dec are similar to Longitude and Latitude

HW Q2: Predict the time difference between the local noon at Iowa City and the local noon at Des Moines. Local noon is defined as the time when the Sun transits the local meridian. You are given the following information: (1) the radius of the Earth is measured to be 6350 km, (2) the distance between Iowa City and Des Moines is 115 miles according to Google Map, and **(3) both Iowa City and Des Moines are at a latitude of +42 degrees**. Choose a sensible unit for your result.

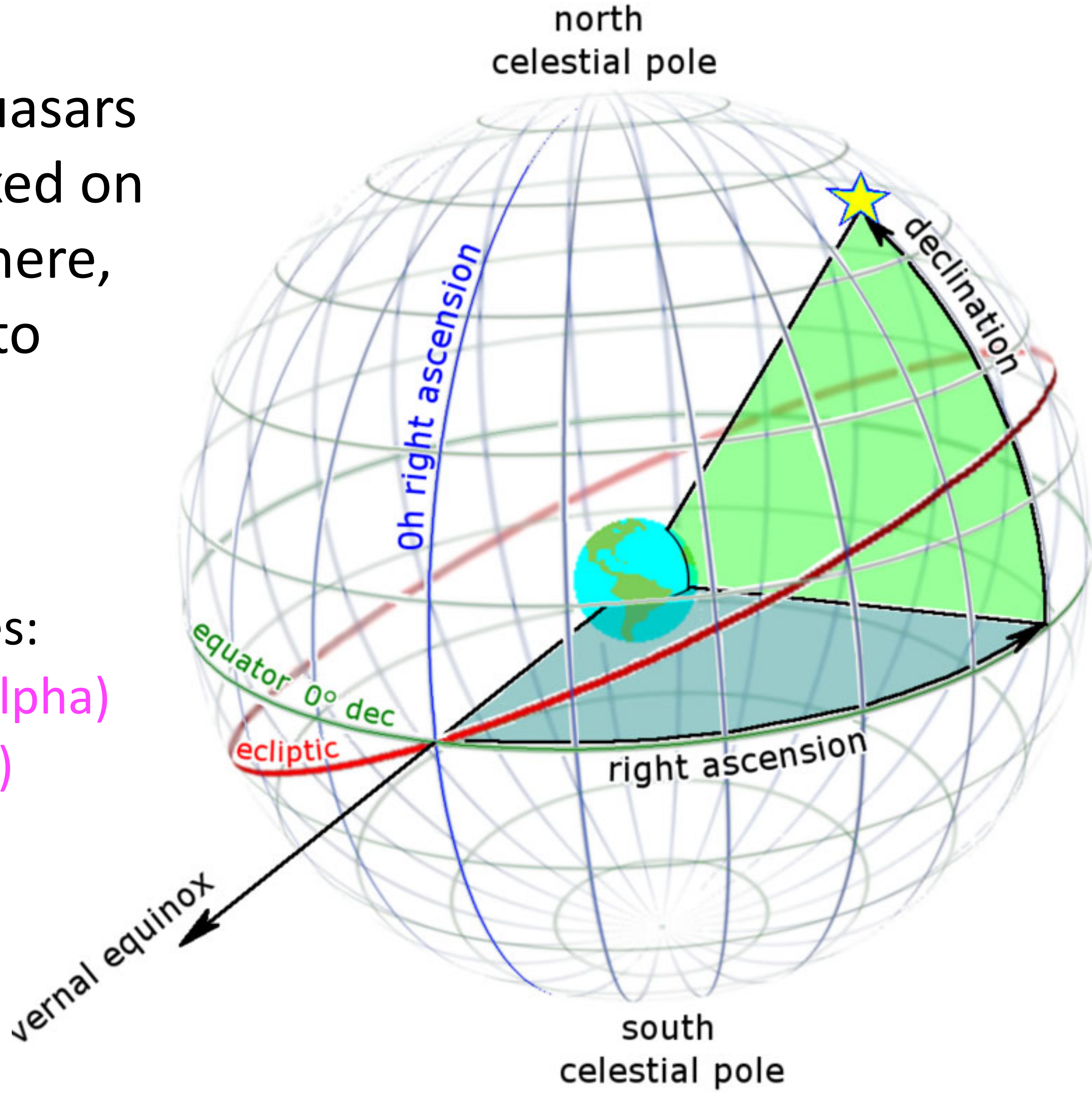
Hint: If you didn't use the latitude, your solution is incorrect.

RA & Dec are similar to Longitude and Latitude

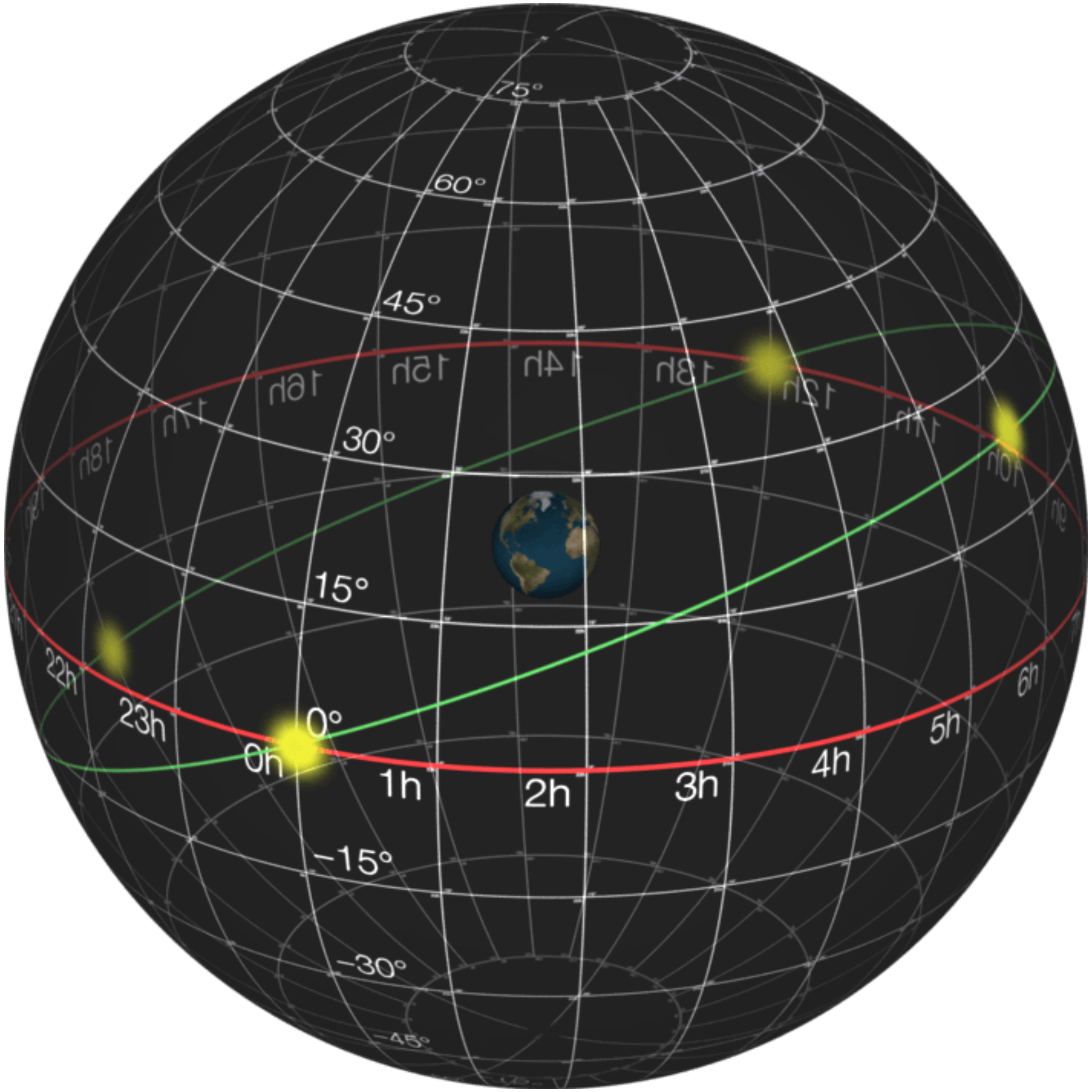


Because stars, galaxies, and quasars appear to be fixed on the celestial sphere, it makes sense to give them fixed coordinates

We use two angles:
right ascension (alpha)
declination (delta)



The Sun and other solar system objects have time-varying coordinates, which are provided as tables called ephemeris



Still with two angles:
right ascension (RA)
declination (Dec)

but as functions of time

Ephemeris of Mars

https://ssd.jpl.nasa.gov/horizons/app.html#/

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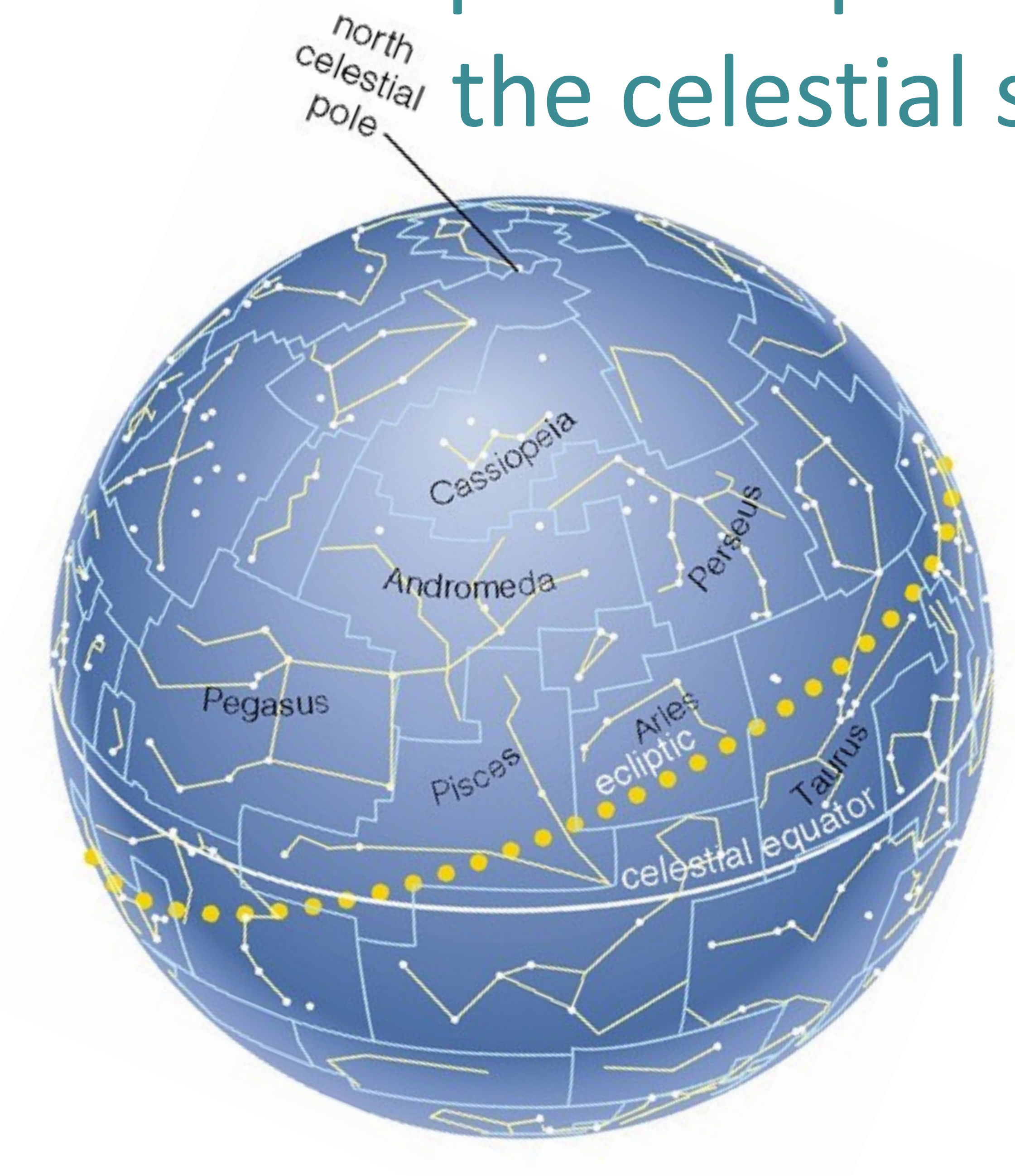
*******************************************************
 Date__(UT)__HR:MN     R.A.____(ICRF)____DEC    APmag
*******************************************************
$$SOE
 2022-Aug-28 00:00     04 09 22.40 +19 36 32.3   -0.040
 2022-Aug-29 00:00     04 11 40.08 +19 43 30.7   -0.052
 2022-Aug-30 00:00     04 13 56.83 +19 50 20.3   -0.061
 2022-Aug-31 00:00     04 16 12.63 +19 57 01.2   -0.064
 2022-Sep-01 00:00     04 18 27.45 +20 03 33.5   -0.075
 2022-Sep-02 00:00     04 20 41.27 +20 09 57.4   -0.102
 2022-Sep-03 00:00     04 22 54.06 +20 16 12.9   -0.123
 2022-Sep-04 00:00     04 25 05.80 +20 22 20.1   -0.152
 2022-Sep-05 00:00     04 27 16.46 +20 28 19.2   -0.175
 2022-Sep-06 00:00     04 29 26.01 +20 34 10.4   -0.196
 2022-Sep-07 00:00     04 31 34.43 +20 39 53.7   -0.195
 2022-Sep-08 00:00     04 33 41.70 +20 45 29.2   -0.218
 2022-Sep-09 00:00     04 35 47.78 +20 50 57.2   -0.244
 2022-Sep-10 00:00     04 37 52.64 +20 56 17.7   -0.257
```

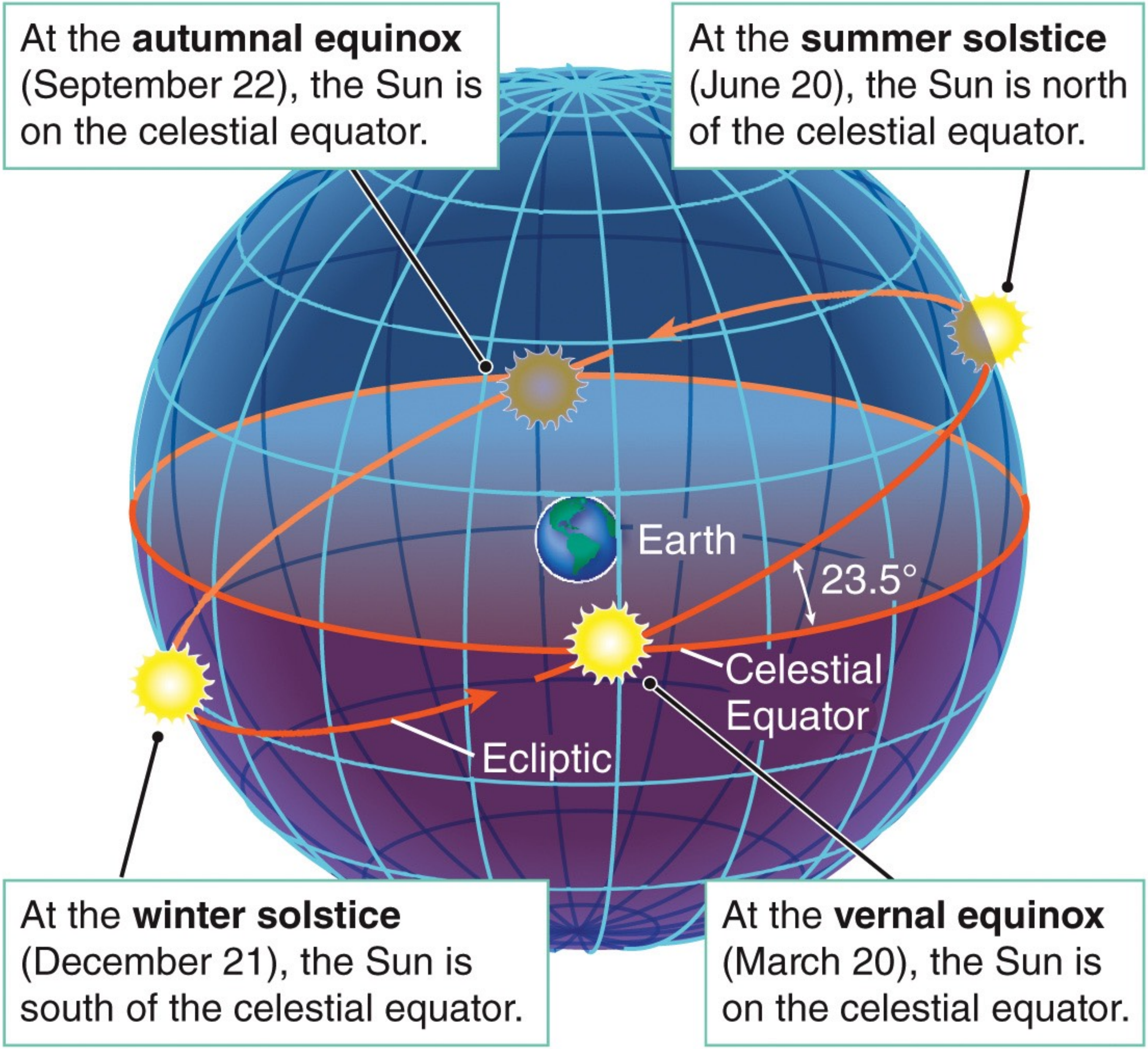
A simplified ephemeris of the Sun

	RA	*Dec*	*Notes*
Spring Equinox (Mar 20)	***0 hr***	***0 deg***	***Origin of Celestial sphere: aka, vernal equinox***
Summer Solstice (Jun 21)	***6 hr***	***+23.5 deg***	***longest day in a year***
Fall Equinox (Sep 22)	***12 hr***	***0 deg***	***equal day and night, same as Spring Equinox***
Winter Solstice (Dec 21)	***18 hr***	***-23.5 deg***	***longest night in a year***

The ecliptic: the path of the Sun on the celestial sphere

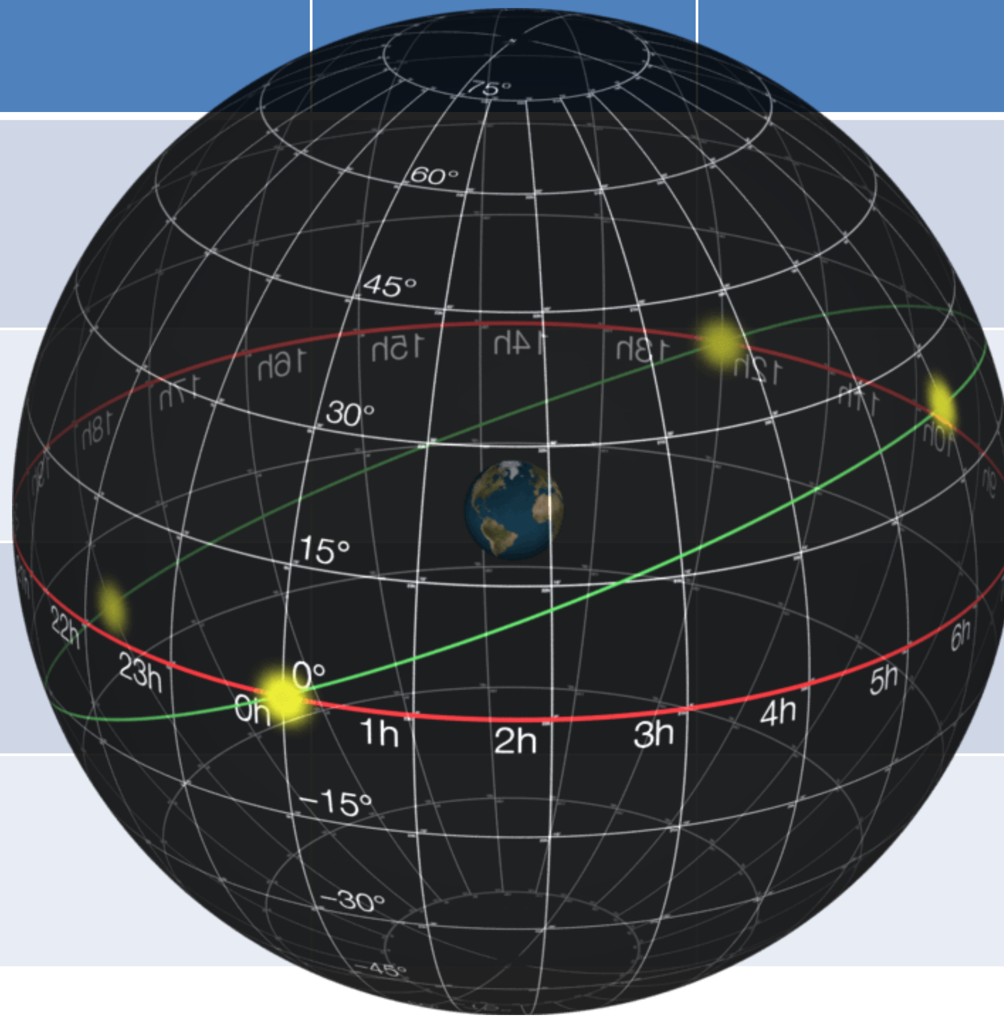


- The ecliptic is tilted 23.5 degrees from the celestial equator, because Earth's spin axis is tilted 23.5 degrees from the plane of its orbit around the Sun

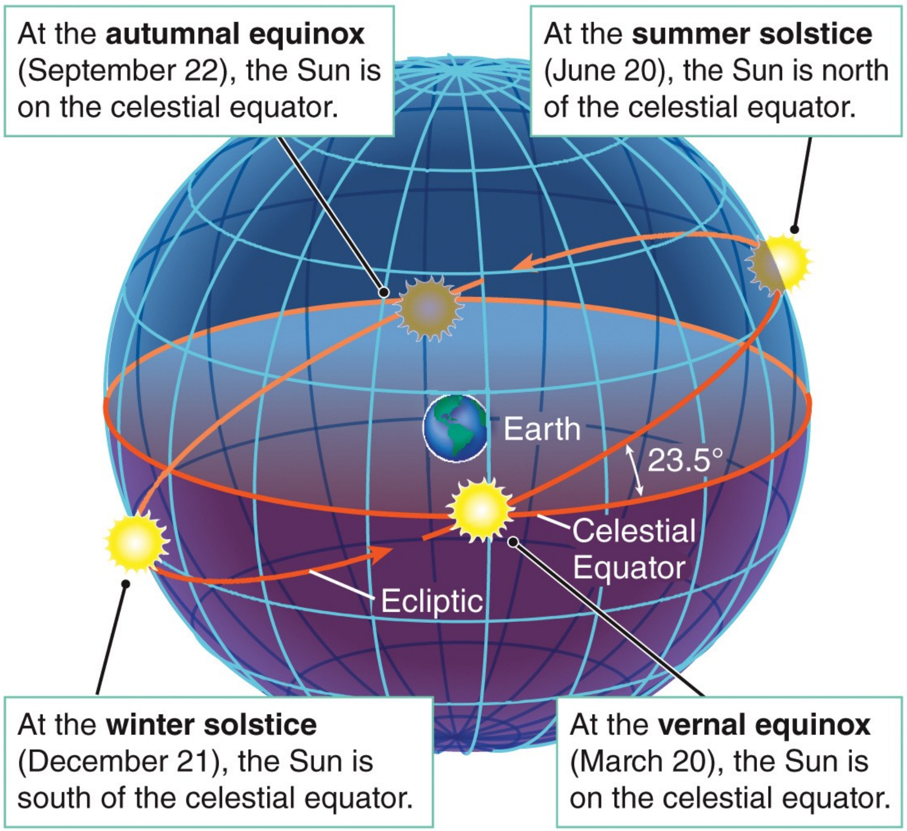

At the **autumnal equinox** (September 22), the Sun is on the celestial equator.
At the **summer solstice** (June 20), the Sun is north of the celestial equator.
Earth
23.5°
Celestial Equator
Ecliptic
At the **winter solstice** (December 21), the Sun is south of the celestial equator.
At the **vernal equinox** (March 20), the Sun is on the celestial equator.

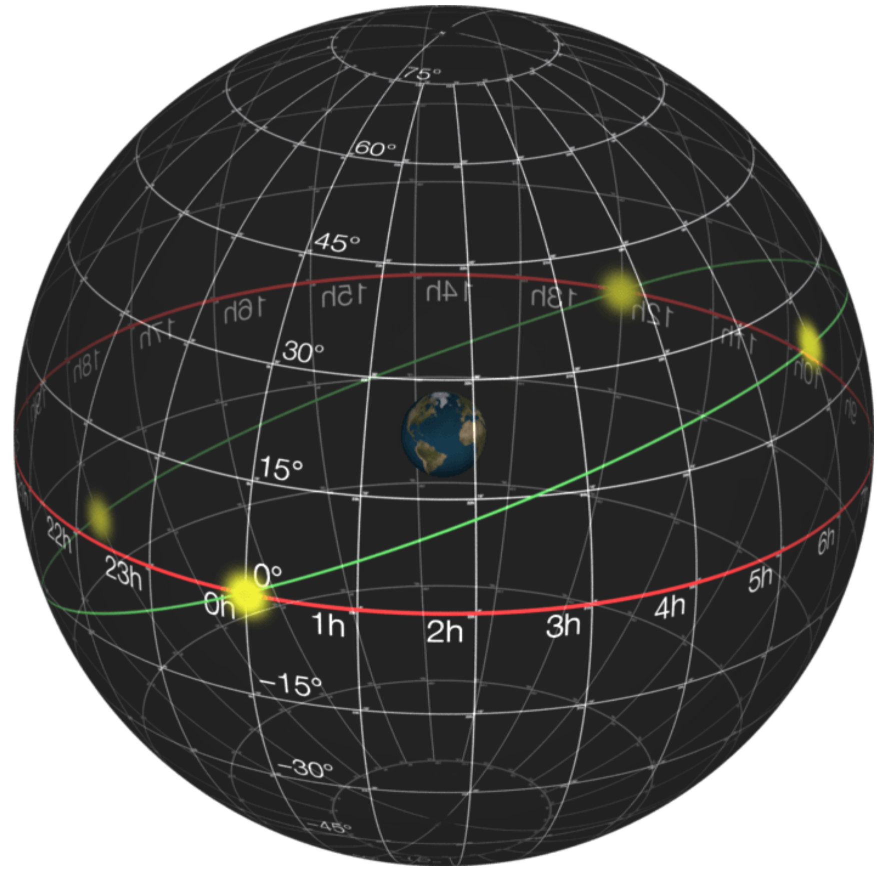
Work out (RA, Dec) coordinates of the Sun on the four special dates

	RA (hours)	***Dec (degrees)***	***Notes***
Spring Equinox (Mar 20)			
Summer Solstice (Jun 21)			
Fall Equinox (Sep 22)			
Winter Solstice (Dec 21)			



- Work out (RA, Dec) coordinates of the Sun on the four special dates





A simplified ephemeris of the Sun

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Spring Equinox (Mar 20)	***0 hr***	***0 deg***	***Origin of Celestial sphere: aka, vernal equinox***
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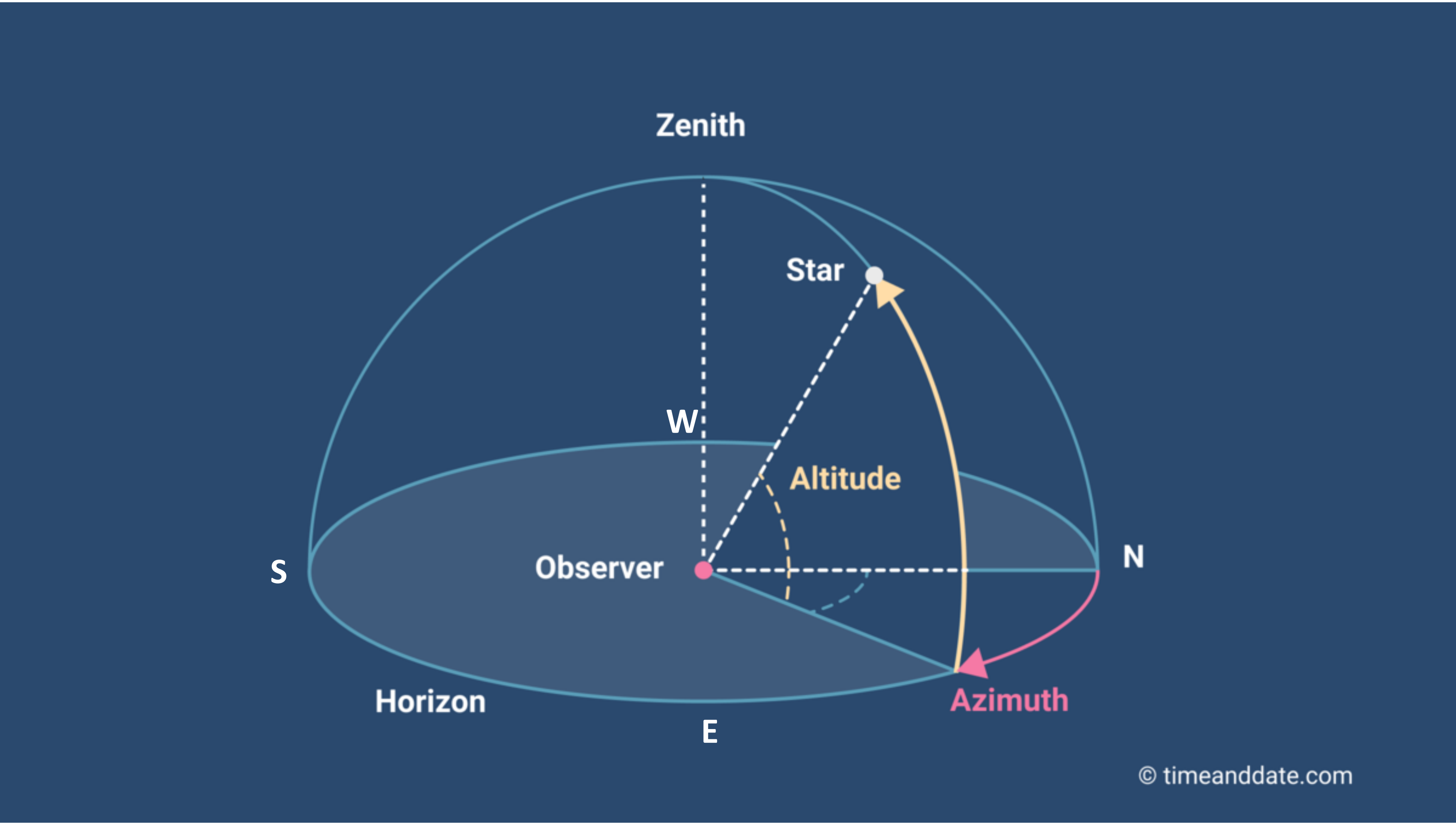
Winter Solstice (Dec 21)	***18 hr***	***-23.5 deg***	***longest night in a year***

Angular coordinates measured by an observer

Altitude and Azimuth (Alt, Az) are what we measure on the ground

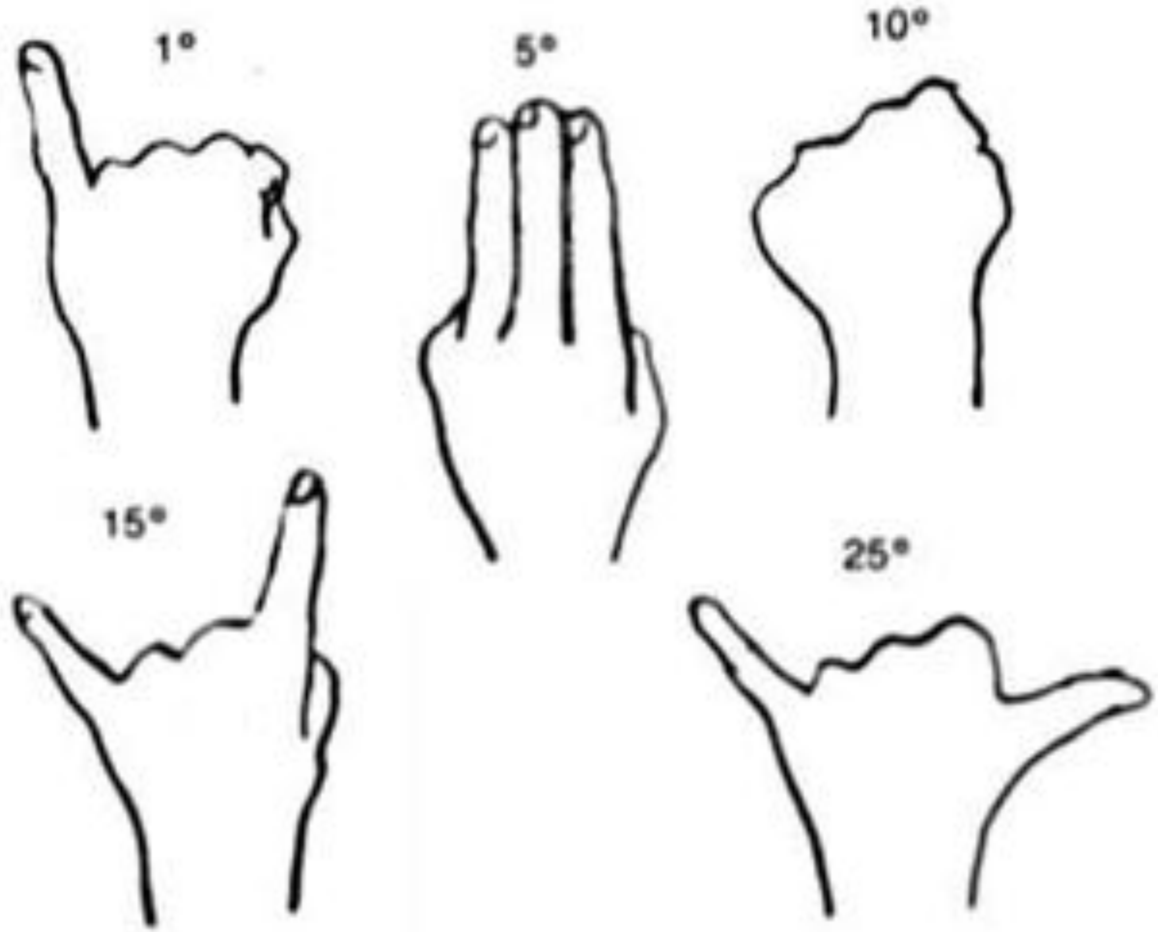
They change all the time: Alt(t), Az(t)

From the perspective of an observer on the ground, each object's direction can be described by another two angles (Alt & Az)



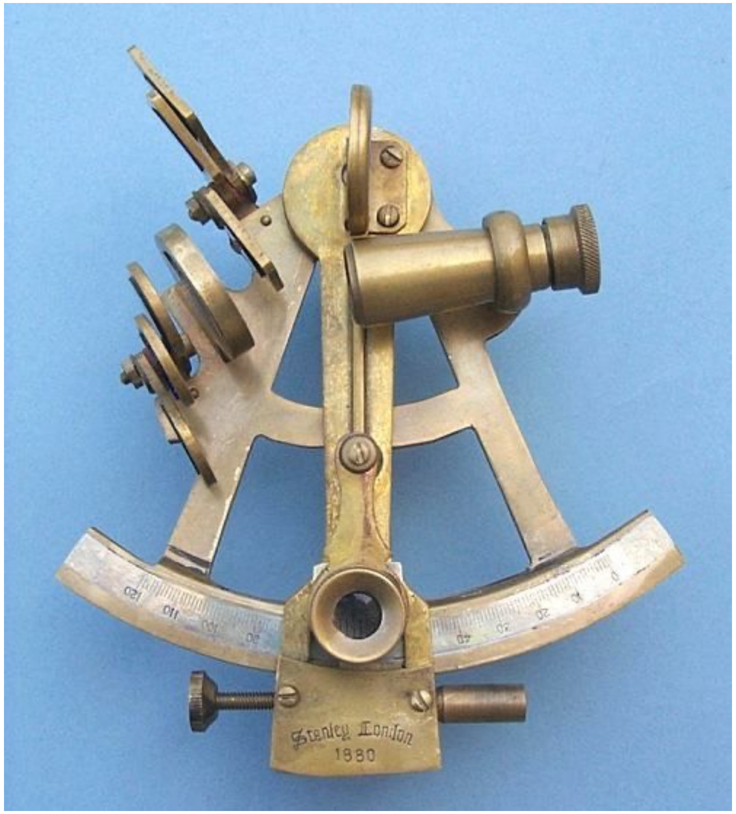
Measuring azimuth with a compass

Measuring altitude with your hand (this week's lab)



U.S. Navy

Measuring **altitude** with a sextant



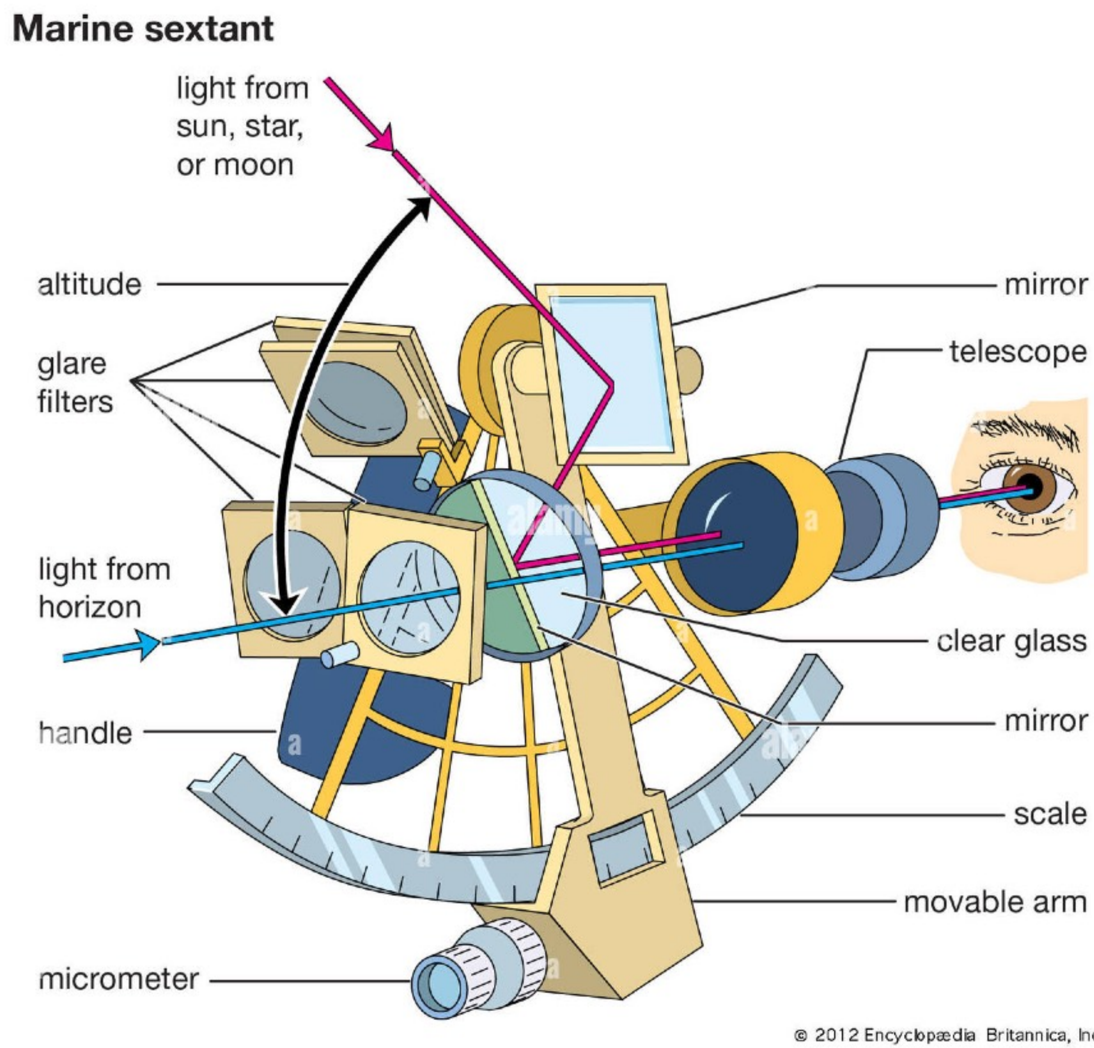
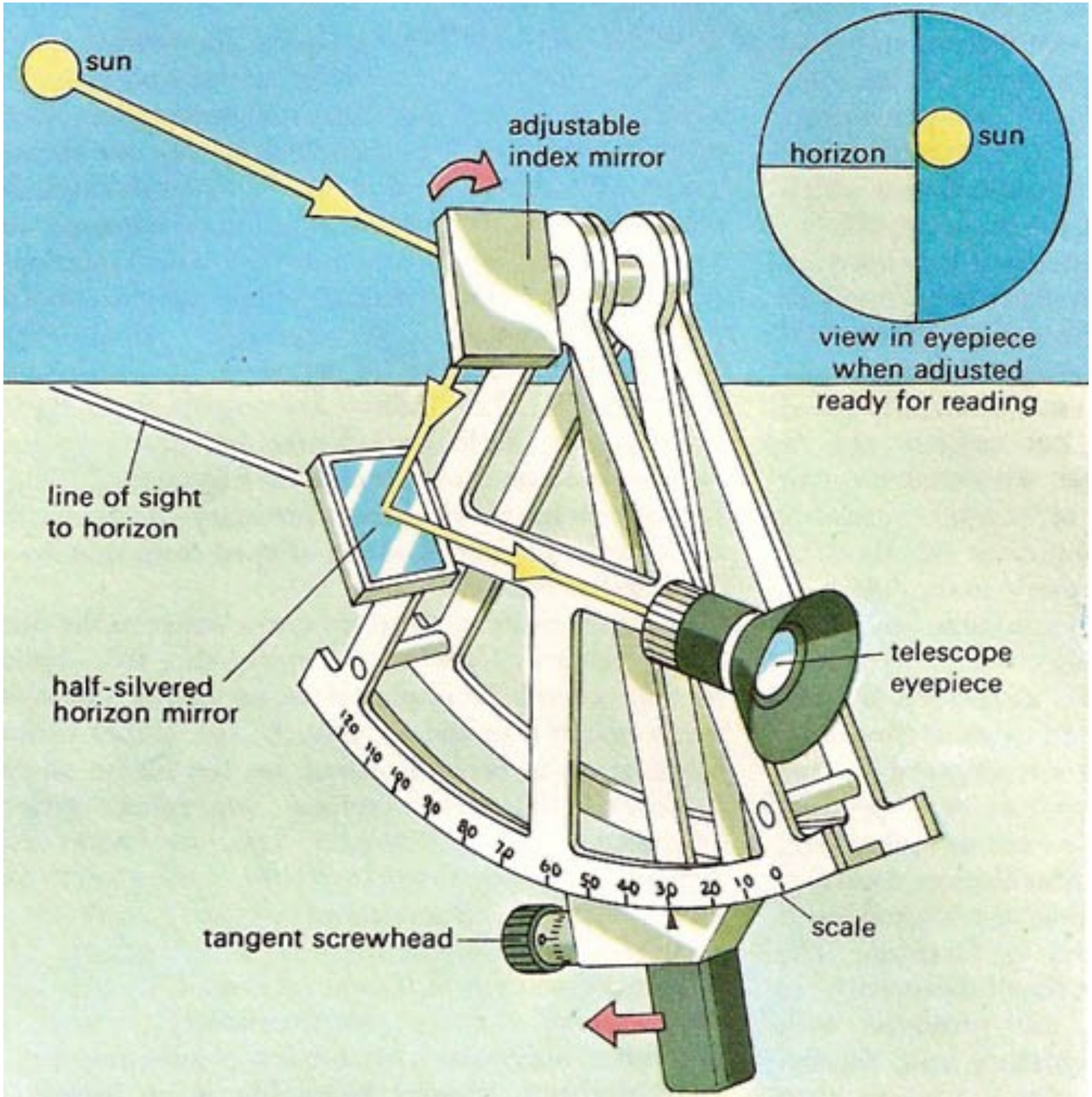


Illustration: How to use sextant to measure the altitude of the Sun



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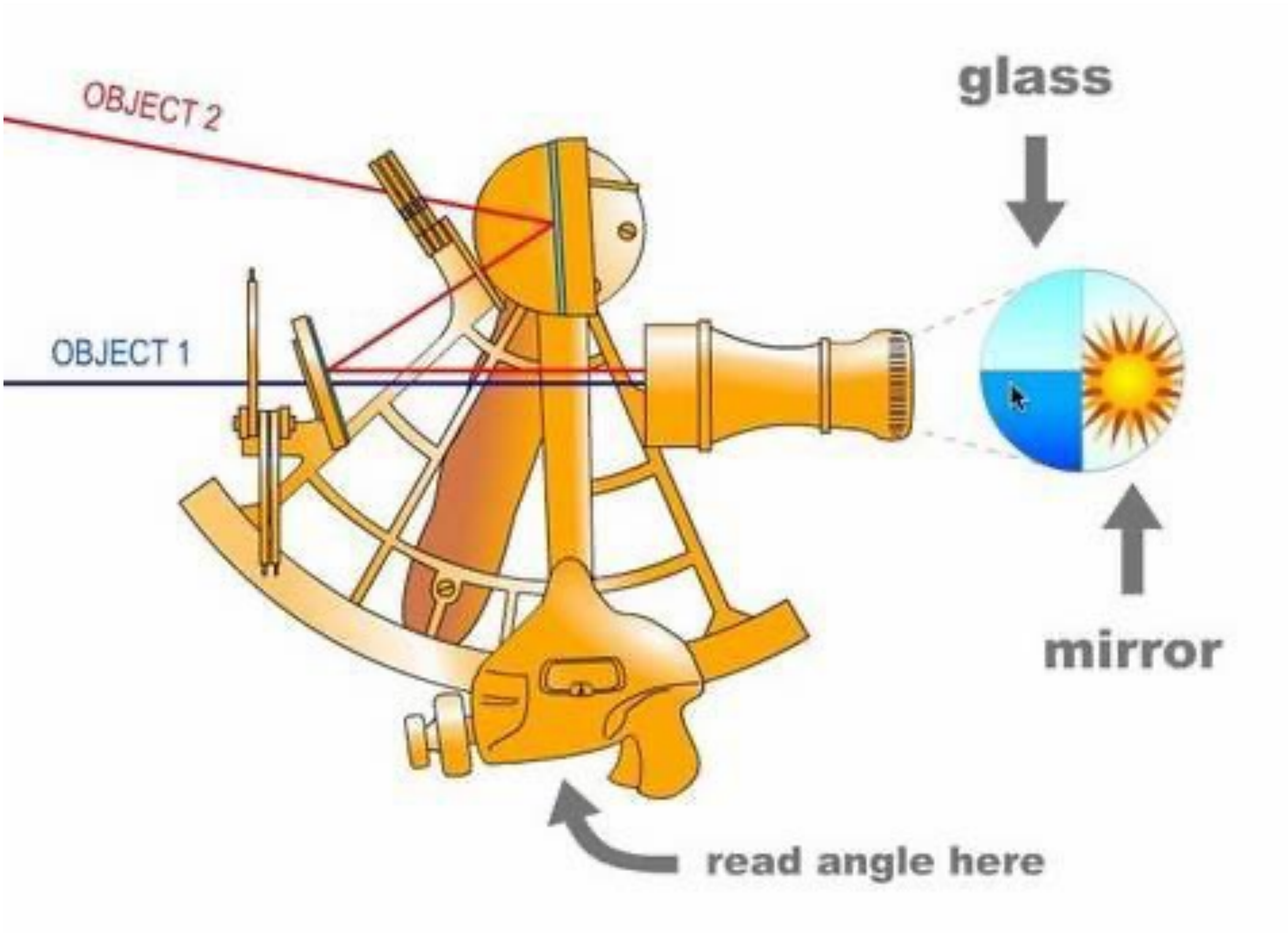
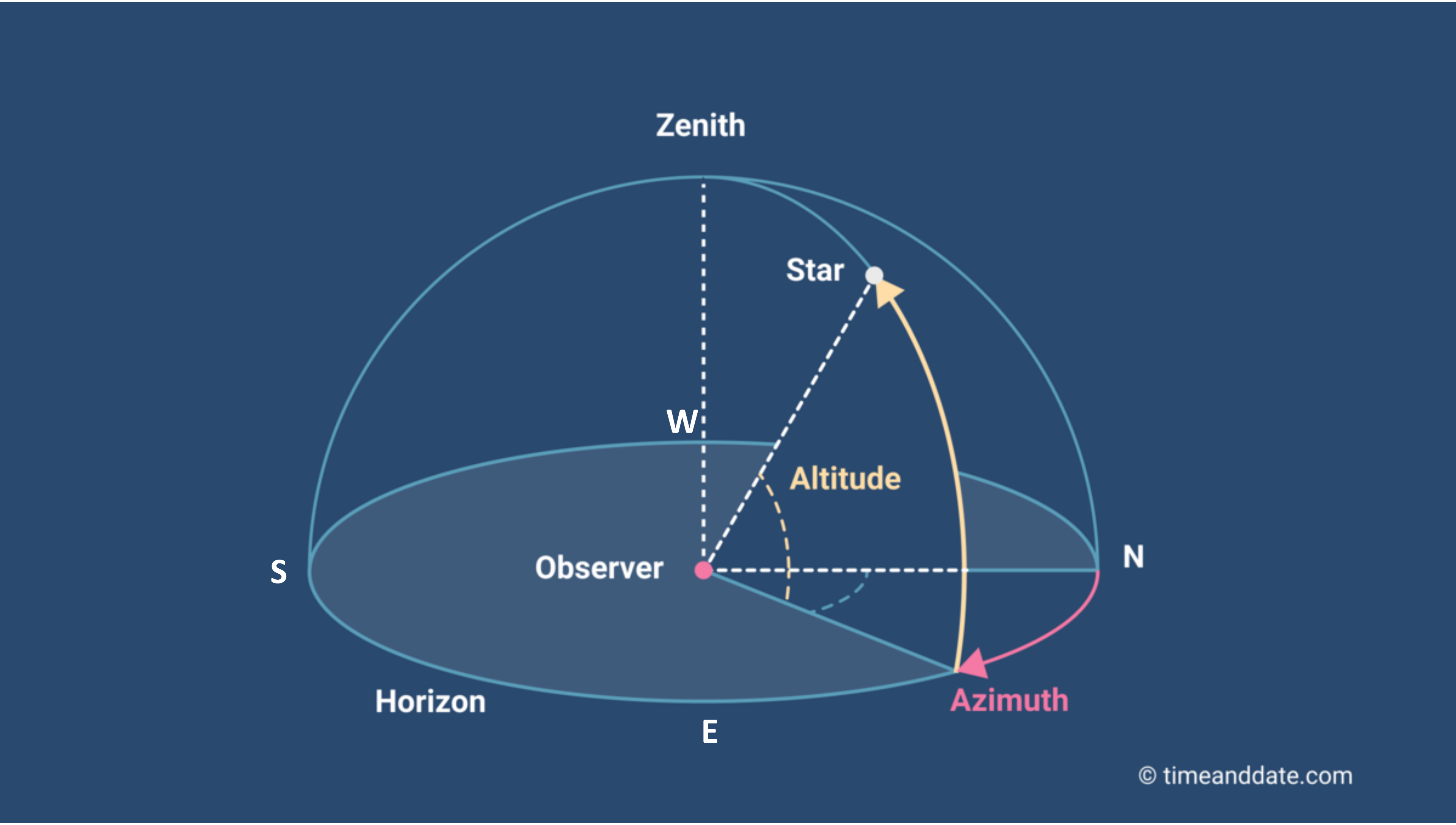
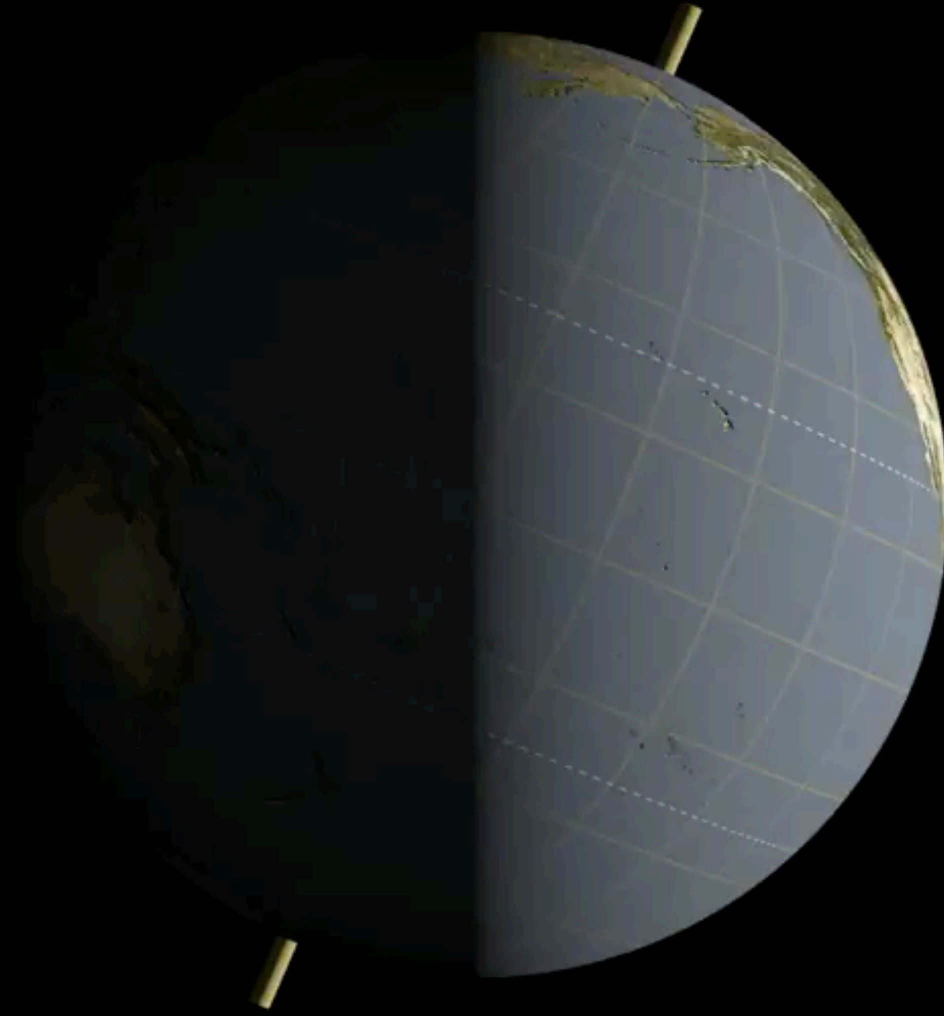


From the perspective of an observer on the ground, each object's direction can be described by another two angles (Alt & Az)



Diurnal (Daily) motion of objects on the sky

The diurnal motion of objects on the sky is caused by Earth's daily spin around its poles



Spin of the Earth, animated for Summer Solstice (around June 20)

Evidence of Earth's Spin: Foucault's Pendulum

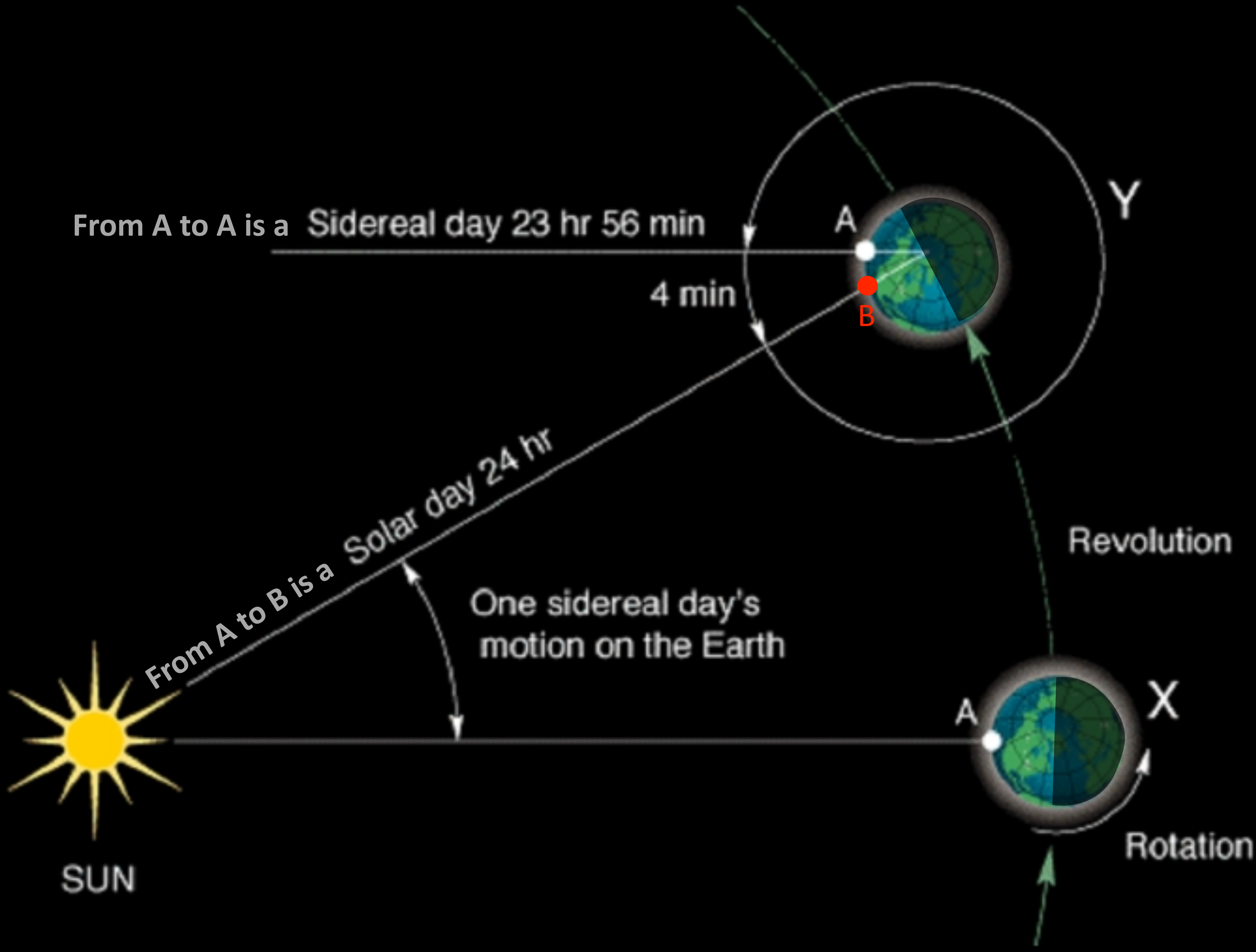
On the pole, Foucault pendulum completes one cycle in 23h56m.

Why not 24h?

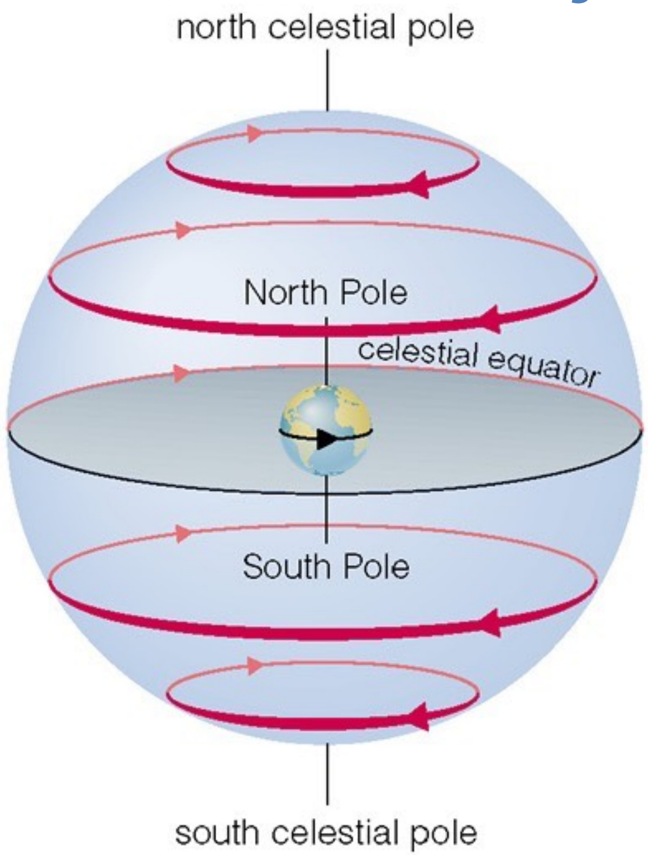
Foucault's pendulum in the Panthéon, Paris (200 ft, 60 lb)

(not the Pantheon in Rome built in 126 CE)

Sidereal Day vs. Solar Day

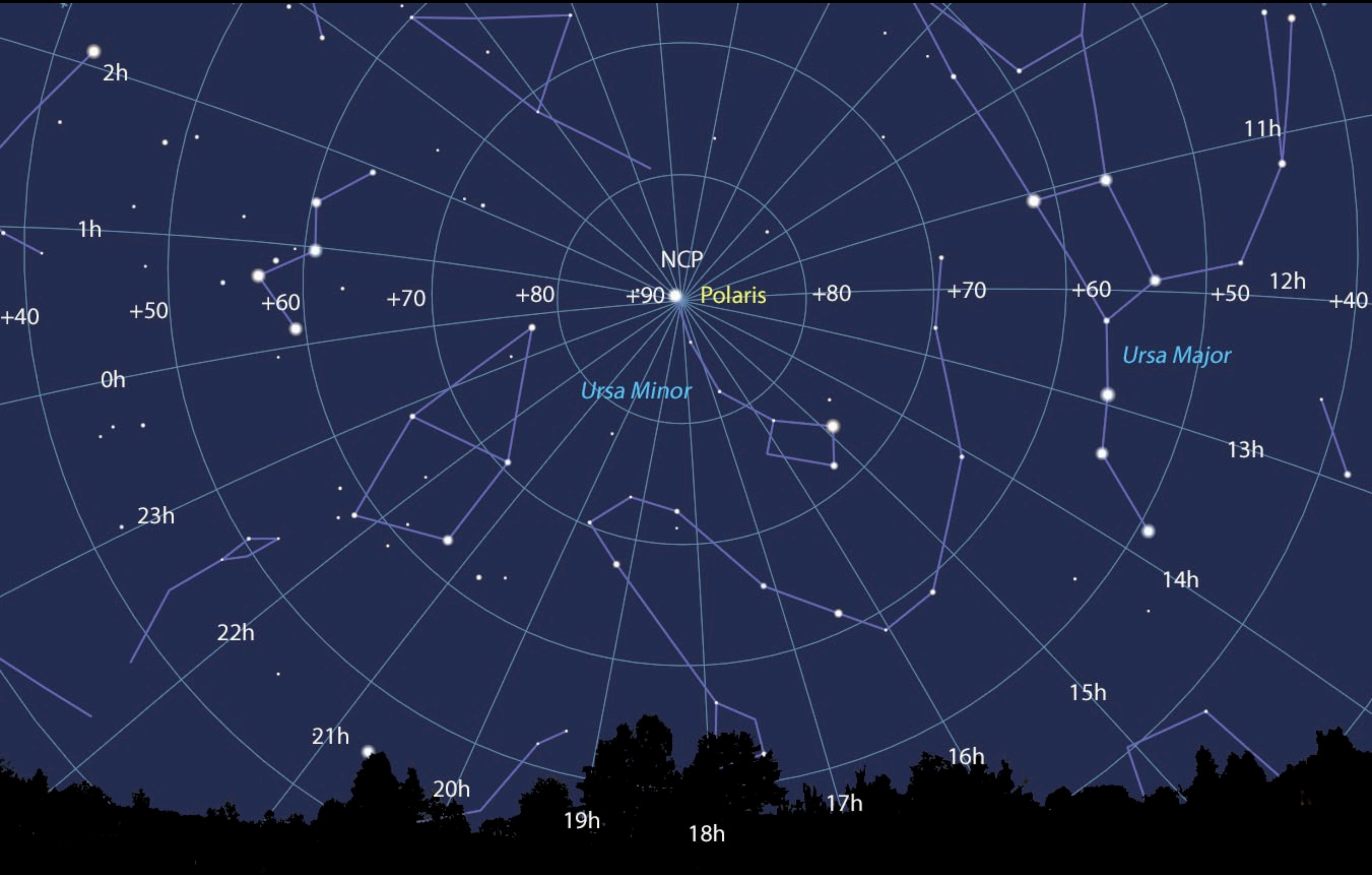


Directions of the diurnal motion of objects on the sky

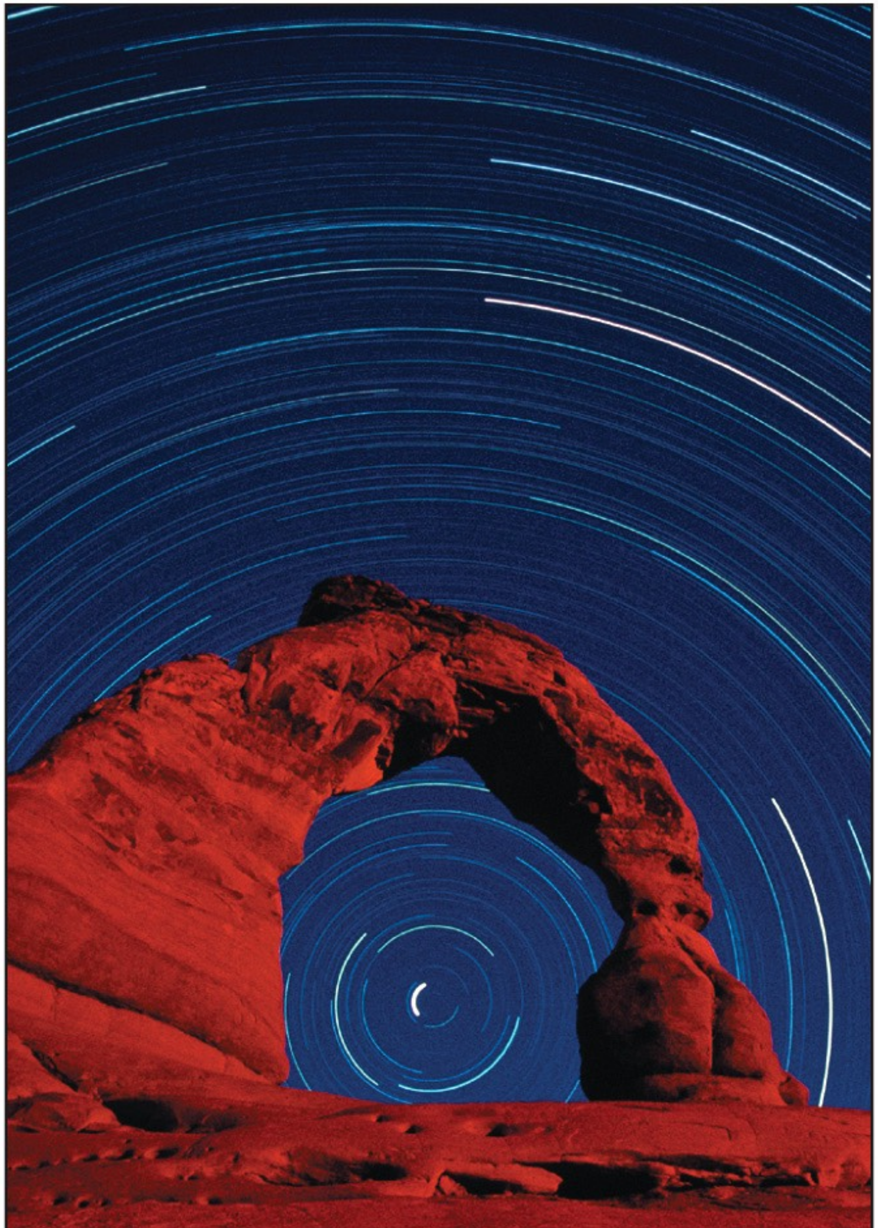


- As the Earth rotates, the sky appears to us to rotate in the opposite direction.
- Imagine you are at the North pole, which direction do stars rotate? CW or CCW? What about the South pole?

Views of the night sky vs. Latitude



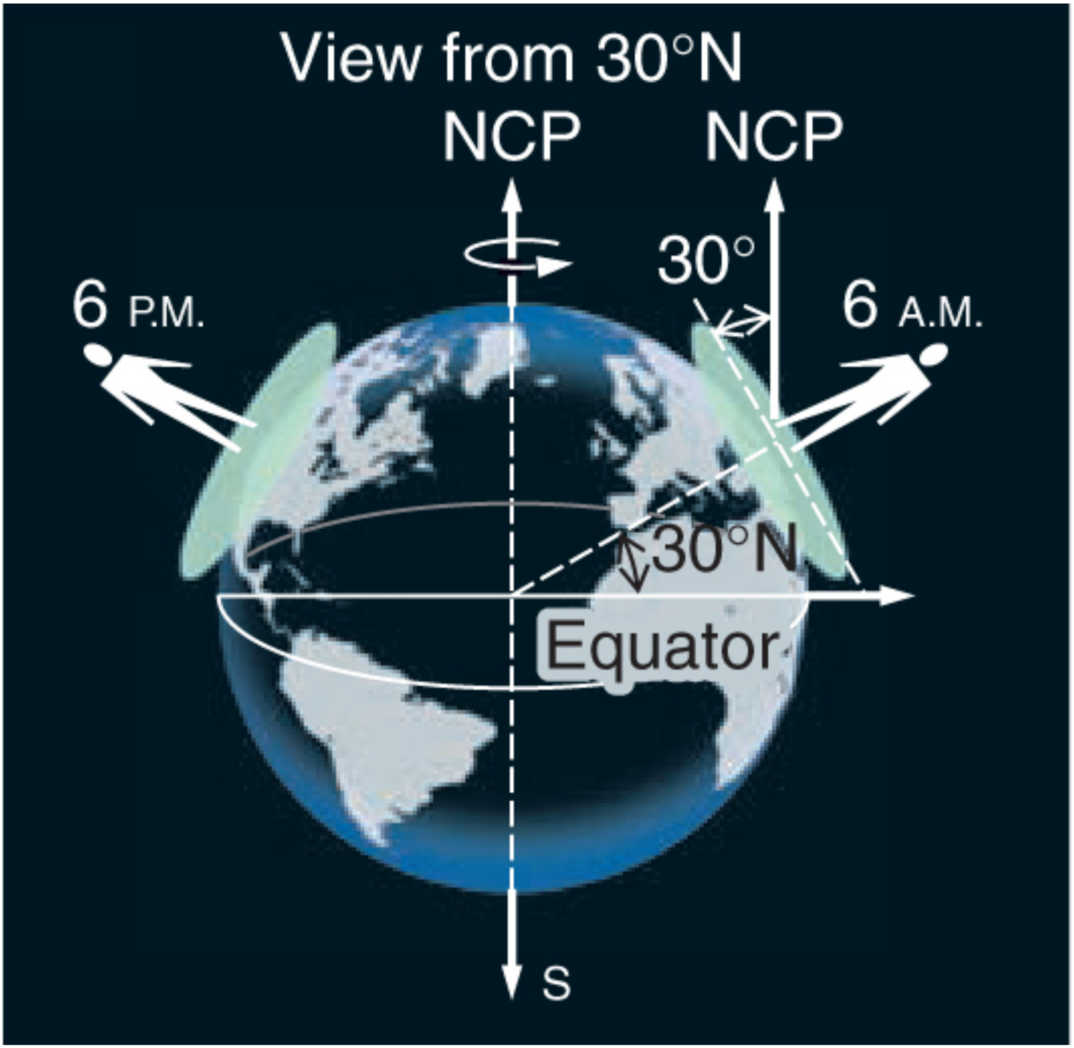
Can you tell which place is at a higher latitude?

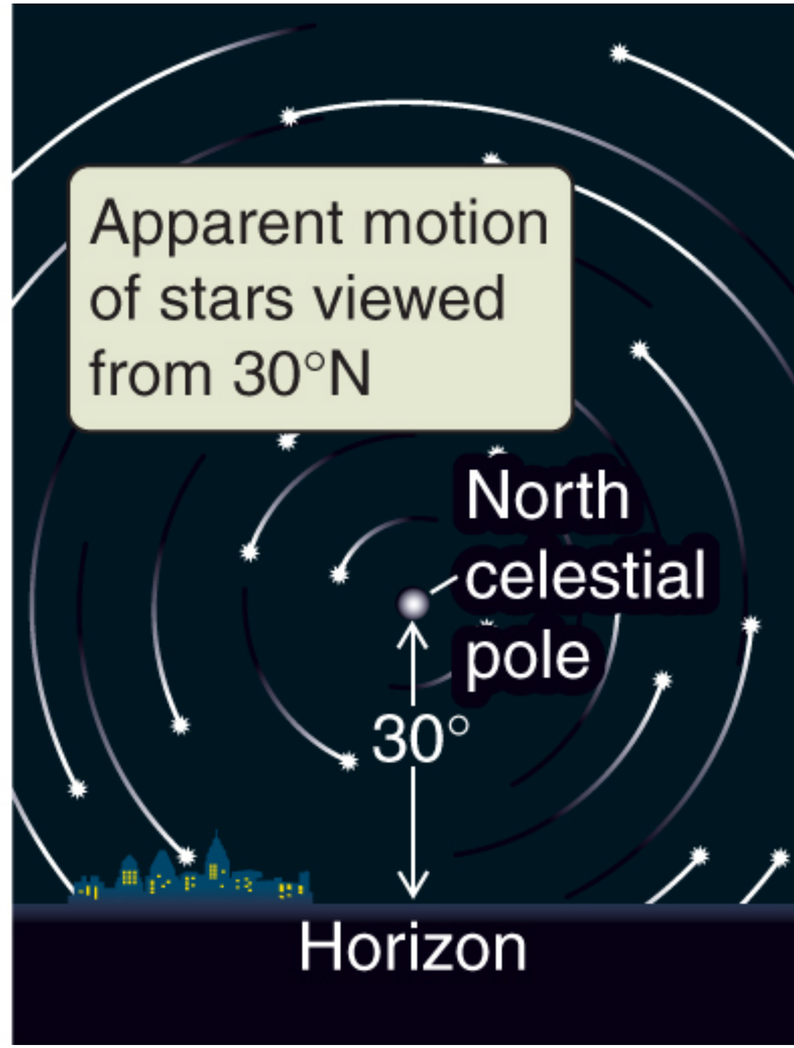


D. Nunuk/Science Source

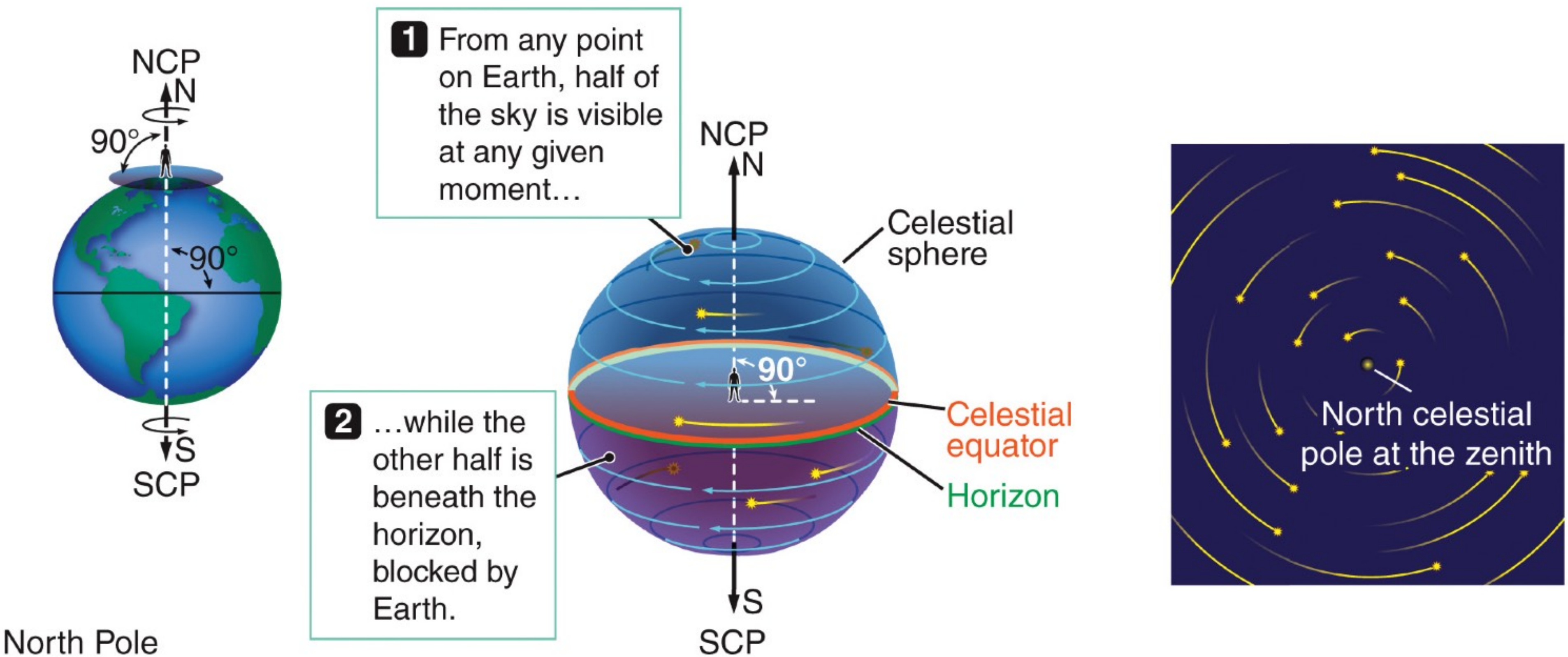
Pekka Parviainen/Science Source

- The altitude of stars depend on its coordinates on the celestial sphere (RA & Dec), the latitude, and the local time of the observer
- From the diagram below, you can see that the altitude of the NCP (close to Polaris) equals the latitude and stars within 30 deg of the NCP never set.

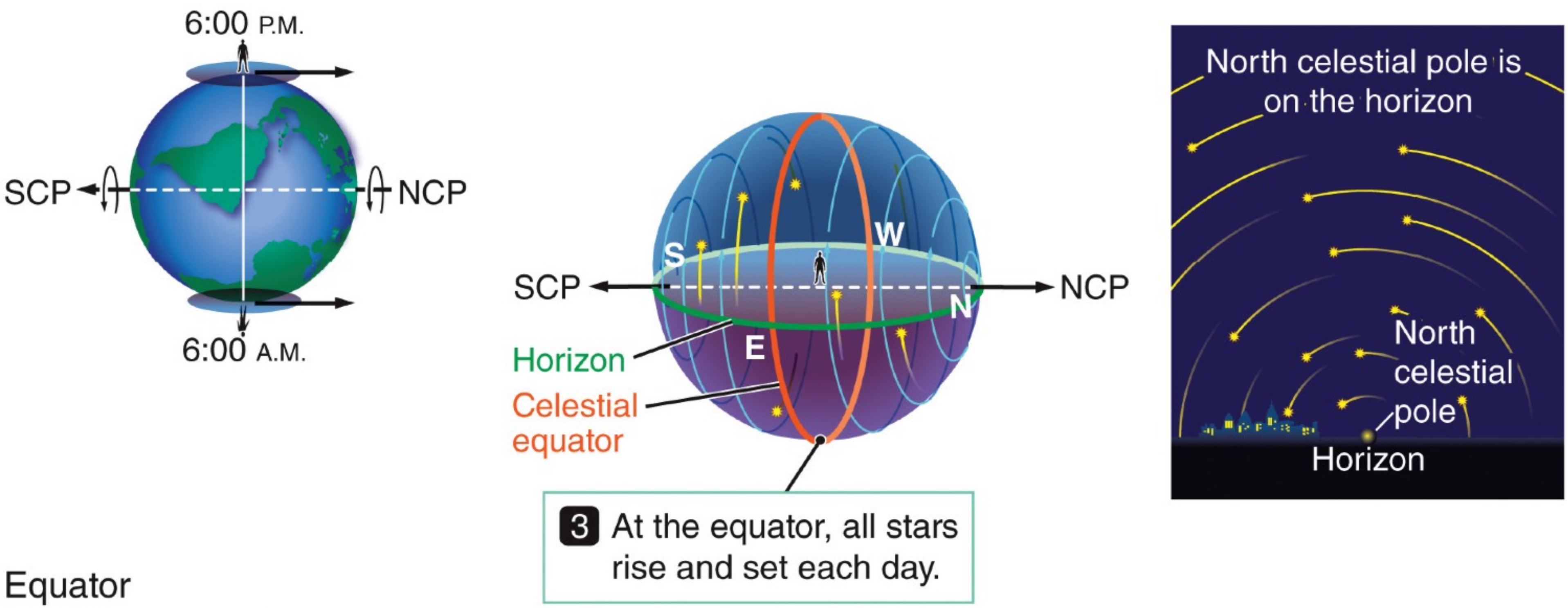




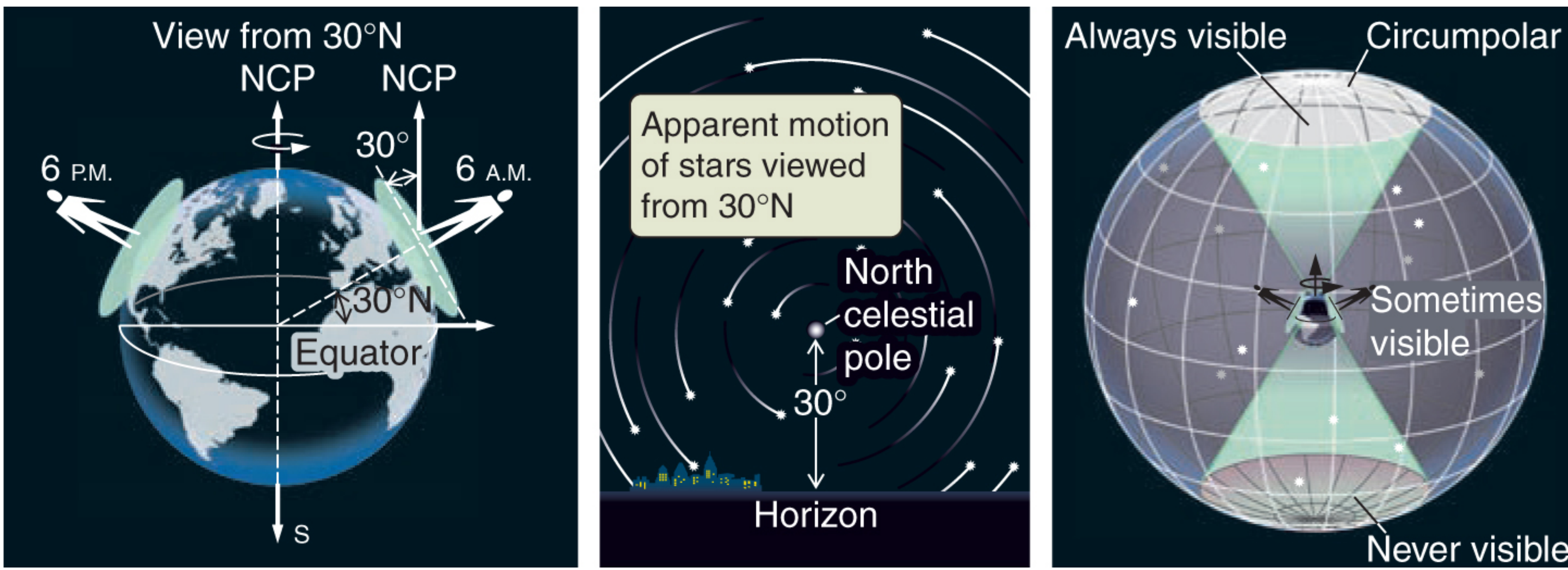
- At Earth's pole, no stars rise and set.
- The celestial pole is at the zenith
- Observers can see half of the celestial sphere as it rotates.
- All visible stars are circumpolar stars



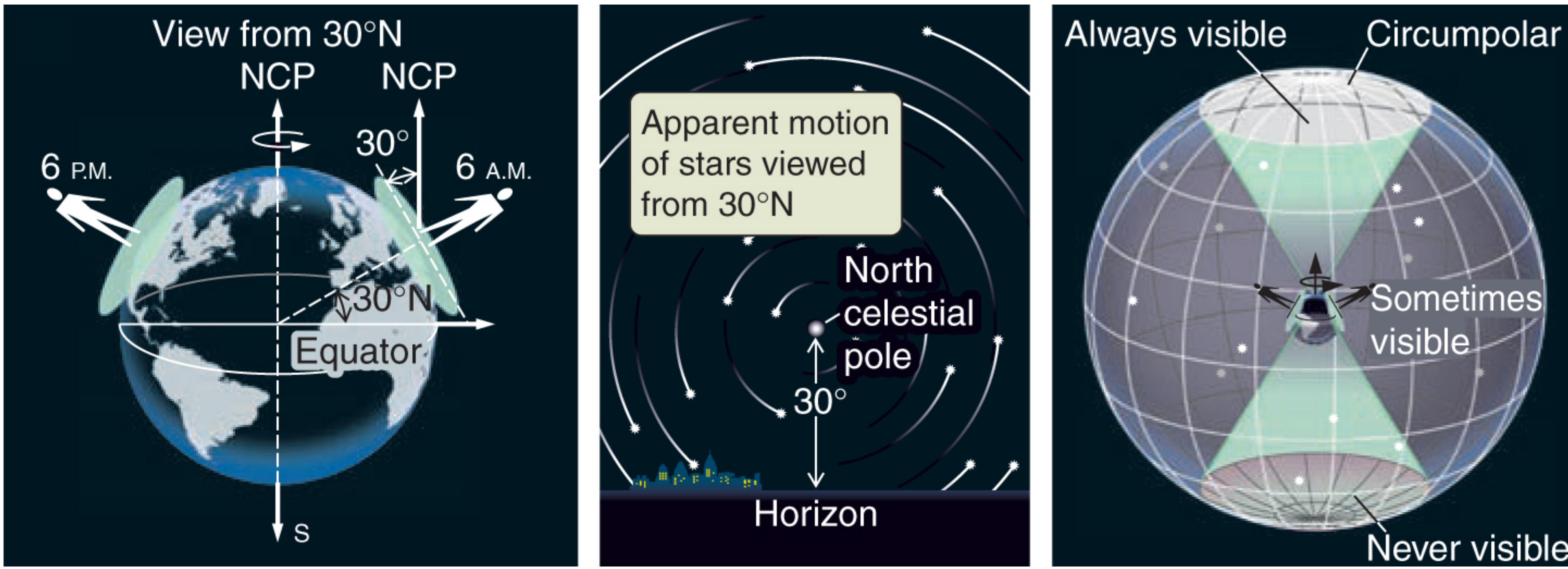
- At Earth's equator, all stars rise and set.
- The celestial poles are on the northern and southern horizons.
- Observers can see the whole celestial sphere as it rotates.
- All stars rise and set, no circumpolar stars



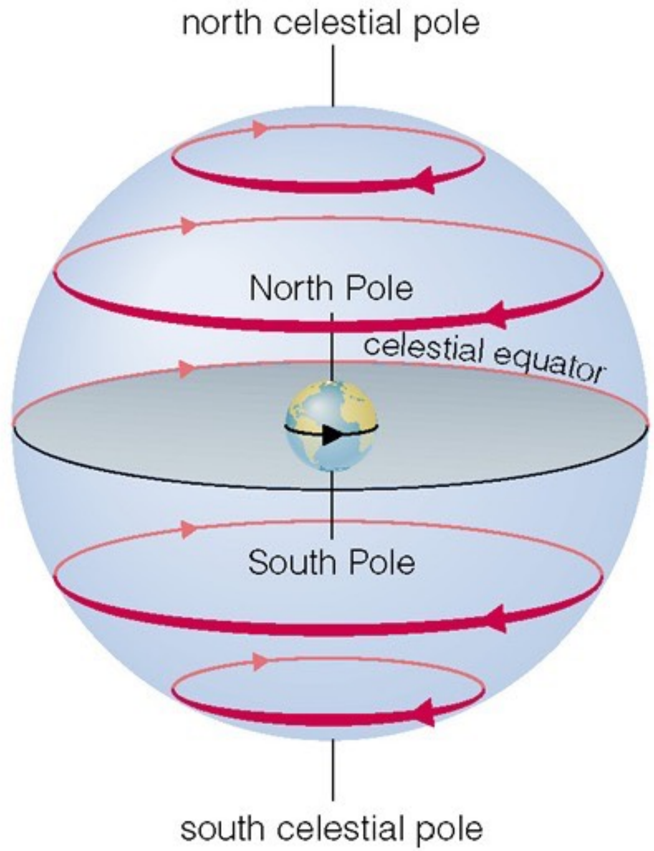
- At intermediate latitudes,
- Some stars are circumpolar (never sets);
  What's their Declination range?
- Some stars rise and set. *What's their Declination range?*
- Some stars are never visible. *What's the Declination range?*



In Iowa City (42° N), which stars are circumpolar? Give their range in Declination.



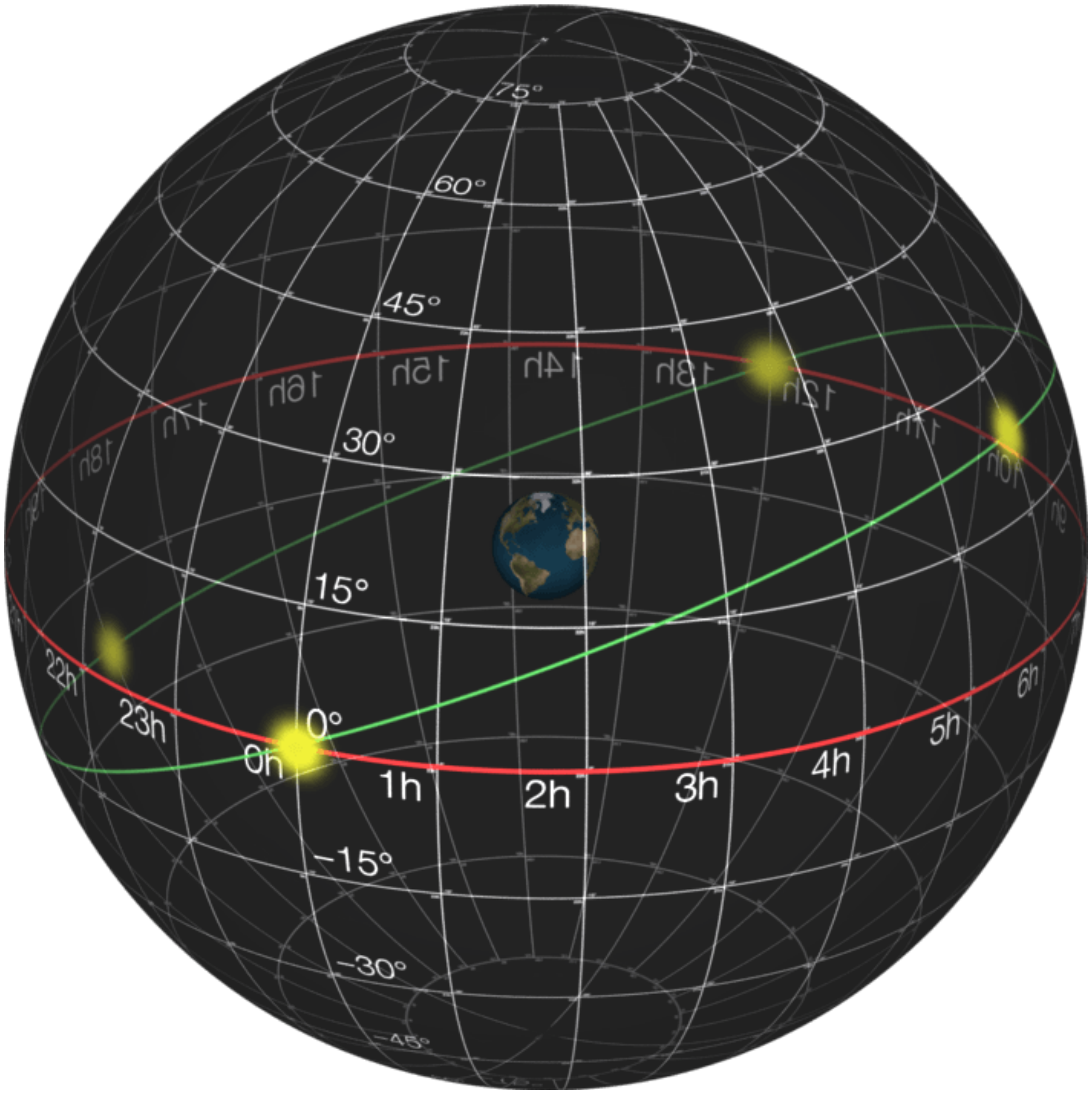
If you're at the south pole, which stars are circumpolar? Give the ranges of RA & Dec.



Recap:

- NCP, SCP, Equator, Ecliptic -> (RA, Dec)
- Horizon, Zenith, Meridian -> (Alt, Az)

Every distant object on the celestial sphere has a *fixed* "longitude & latitude" called RA and Dec.



The celestial sphere of (RA & Dec) is **aligned** with Earth's (Lon, Lat).

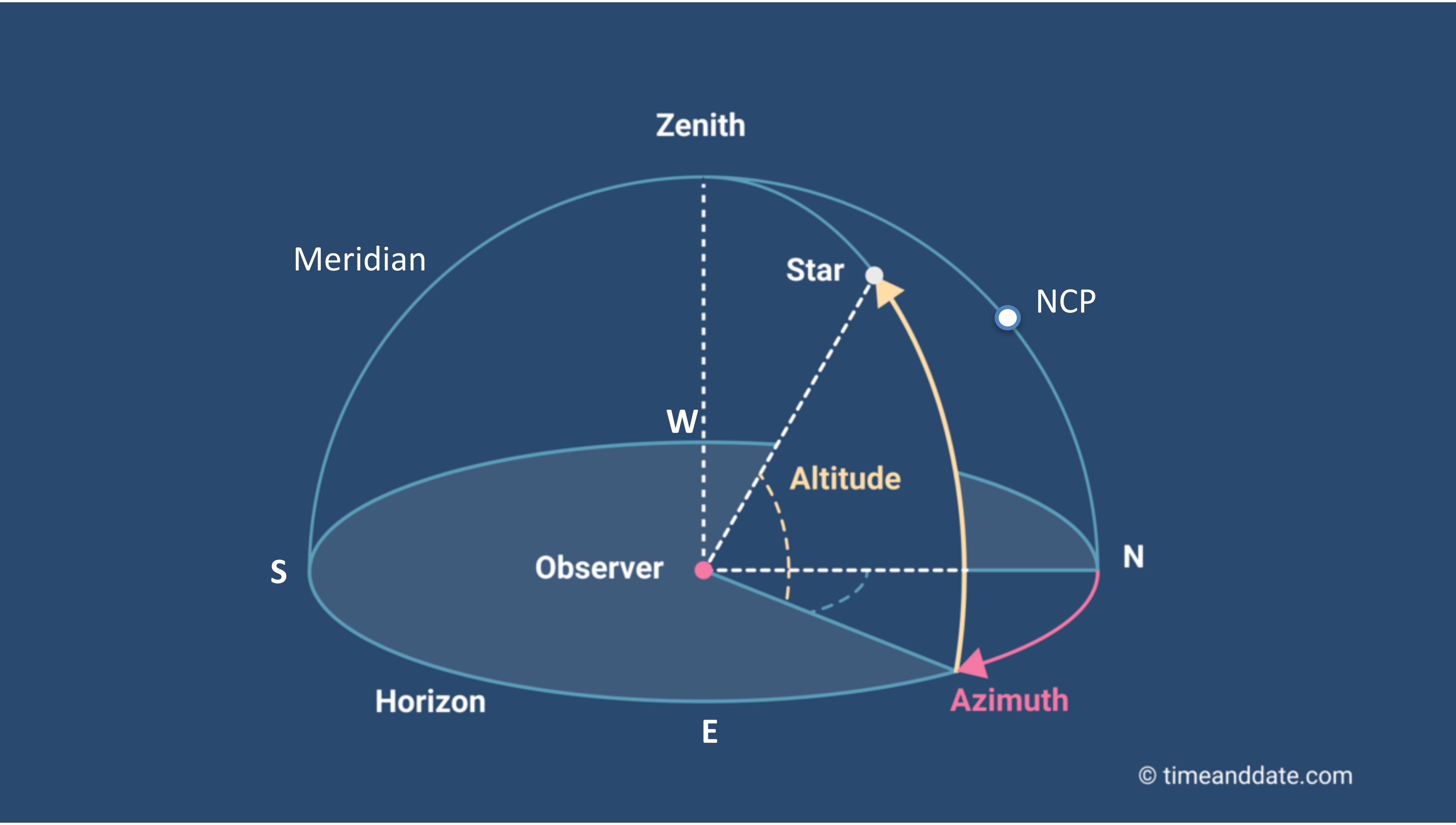
The two spheres **rotate relative to each other** because of Earth's spin, on a period called a **sidereal day** (shorter than a **solar day** by ~4 minutes)

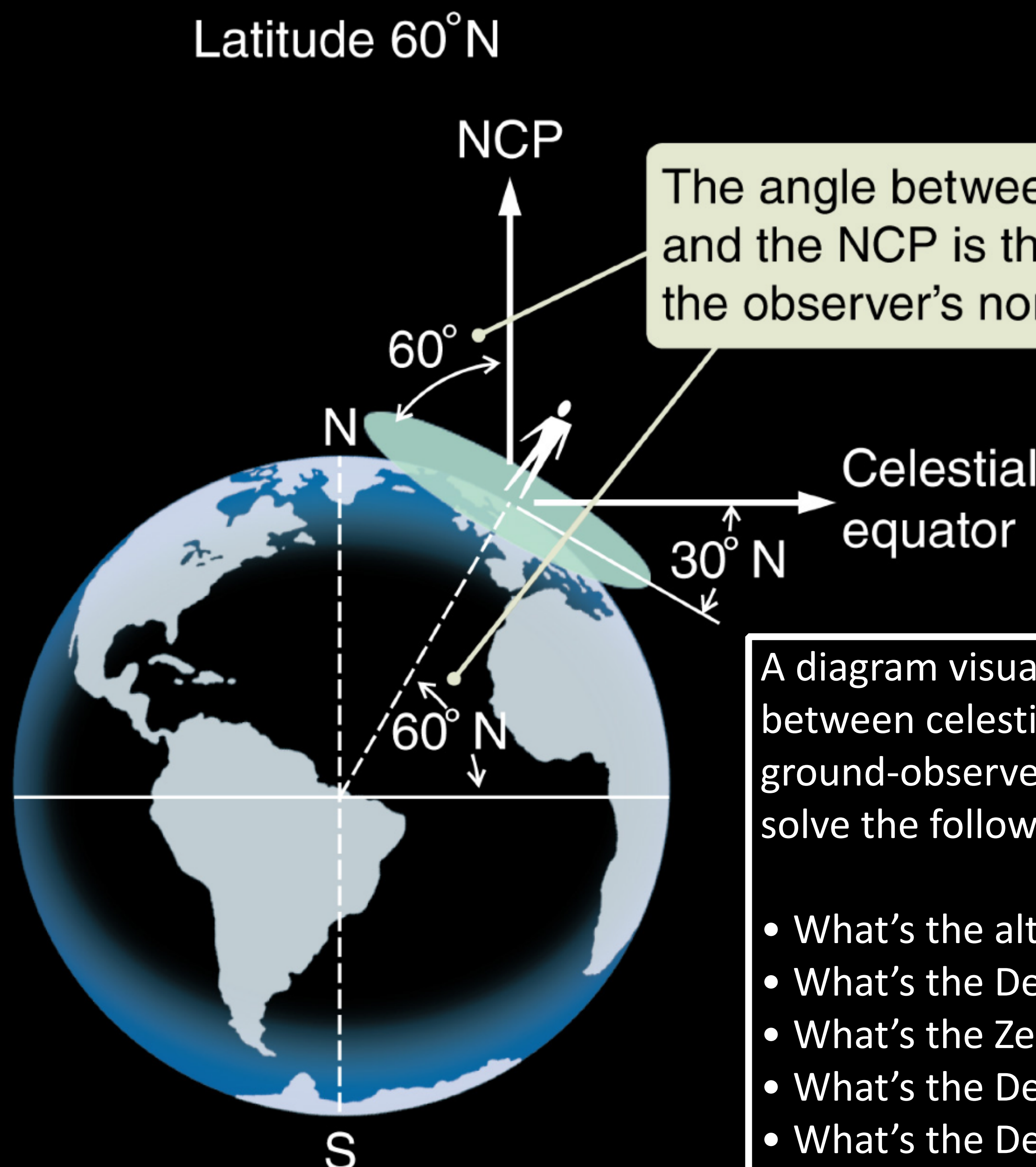
RA & Dec of a distant object *does* change significantly over centuries

A simplified ephemeris of the Sun

	RA	*Dec*	*Notes*
Spring Equinox (Mar 20)	*0 hr*	*0 deg*	*Origin of Celestial sphere: aka, vernal equinox*
Summer Solstice (Jun 21)	*6 hr*	*+23.5 deg*	*longest day in a year*
Fall Equinox (Sep 22)	*12 hr*	*0 deg*	*equal day and night, same as Spring Equinox*
Winter Solstice (Dec 21)	*18 hr*	*-23.5 deg*	*longest night in a year*

Separately from (RA, Dec), each object's direction from the perspective of an observer on the ground are described with another two angles (Alt & Az)





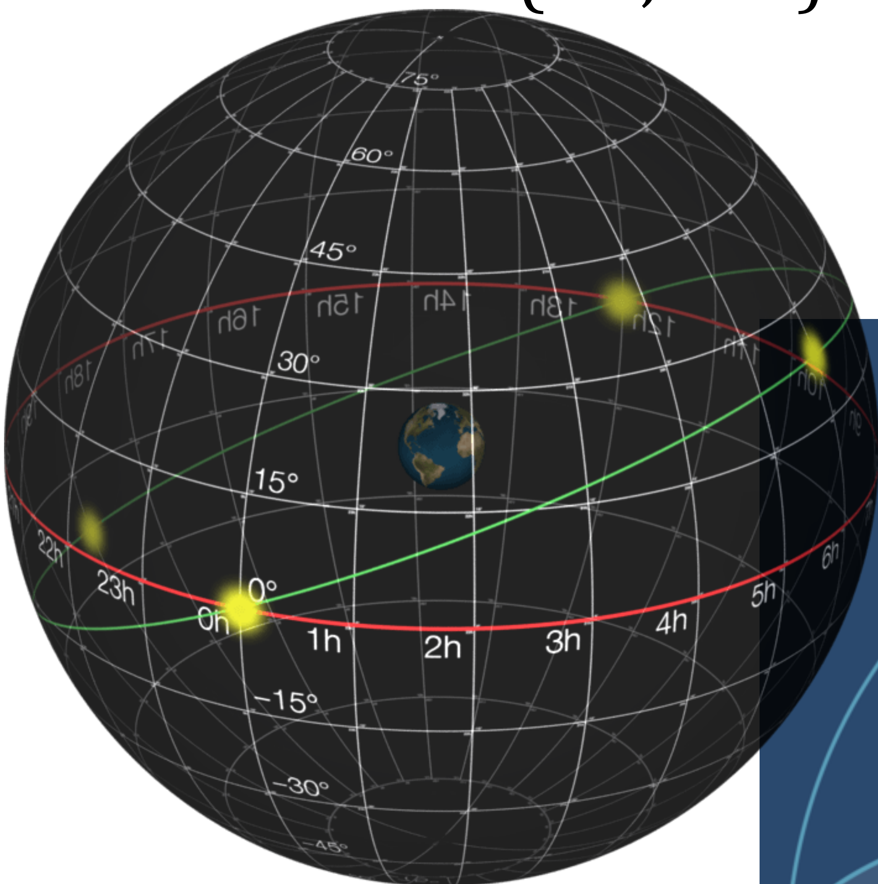
A diagram visualizing the relationship between celestial coordinates (RA, Dec) and ground-observer coordinates (Alt, Az). It helps solve the following problems:

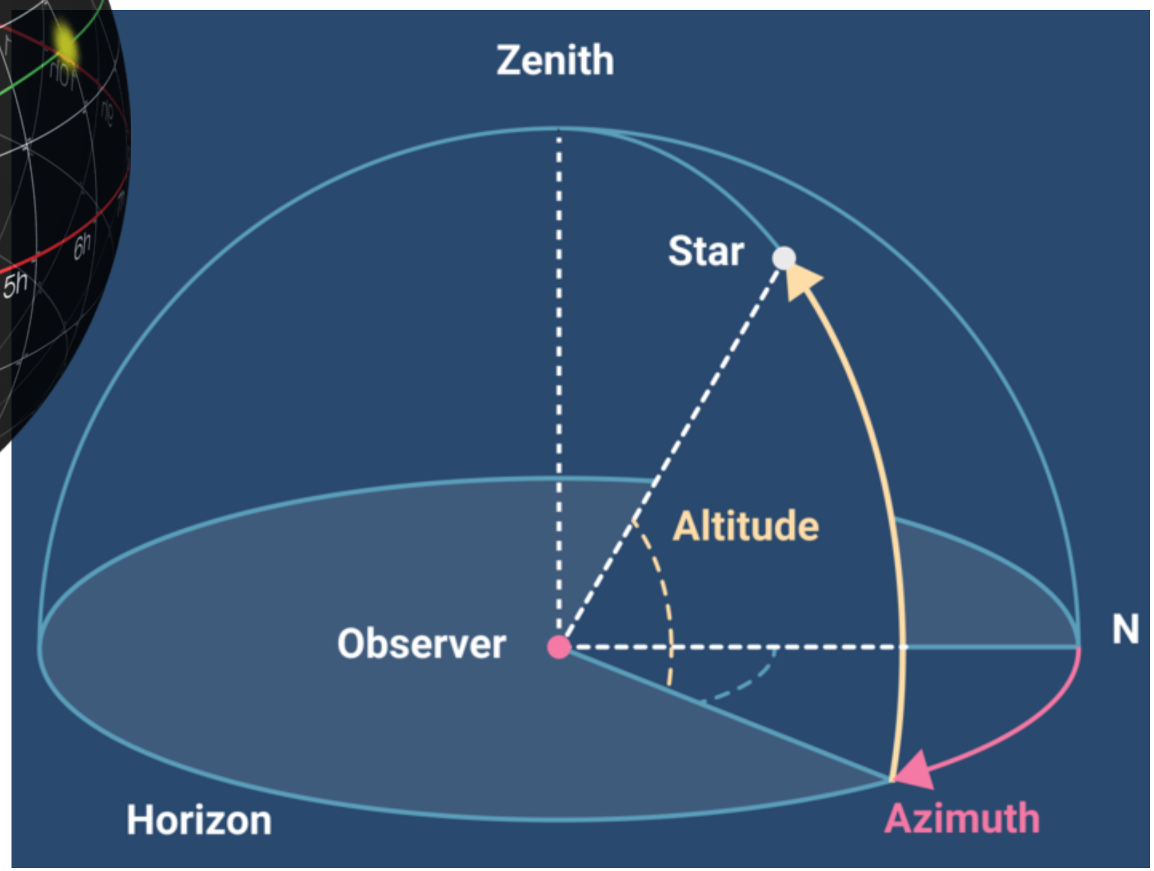
- What's the altitude of NCP?
- What's the Decl. of the zenith?
- What's the Zenith Angle of the Sun at noon?
- What's the Decl. range of circumpolar stars?
- What's the Decl. range of unobservable stars?

Simple Coordinate Conversion

for special locations or sources

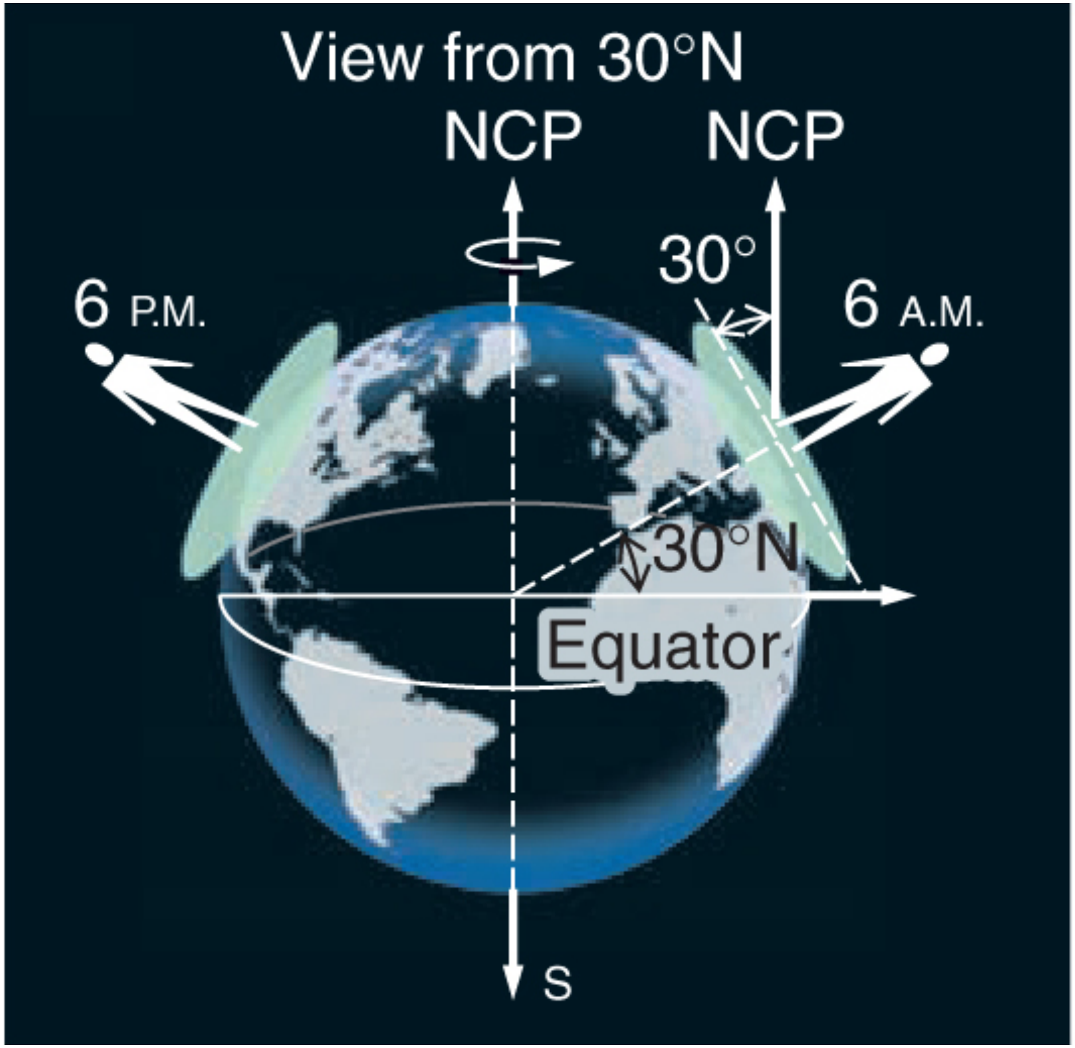
How do we put the two sets of coordinates together?
(RA, Dec) vs. [Alt(t), Az(t)]

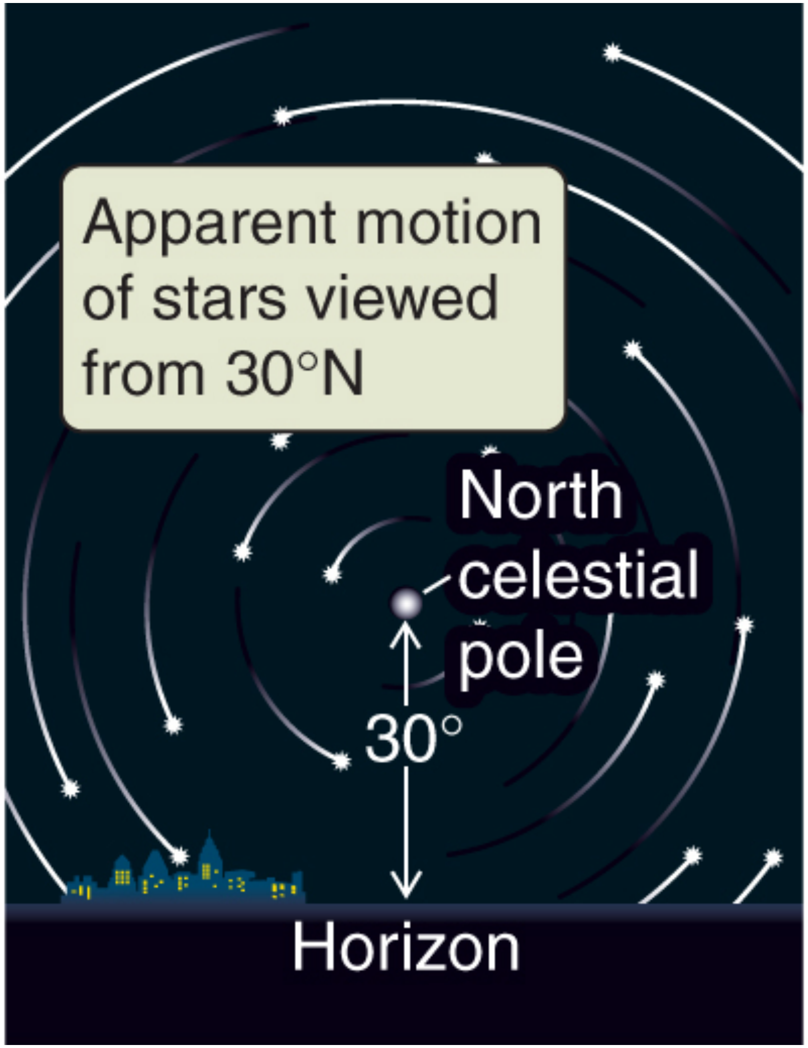




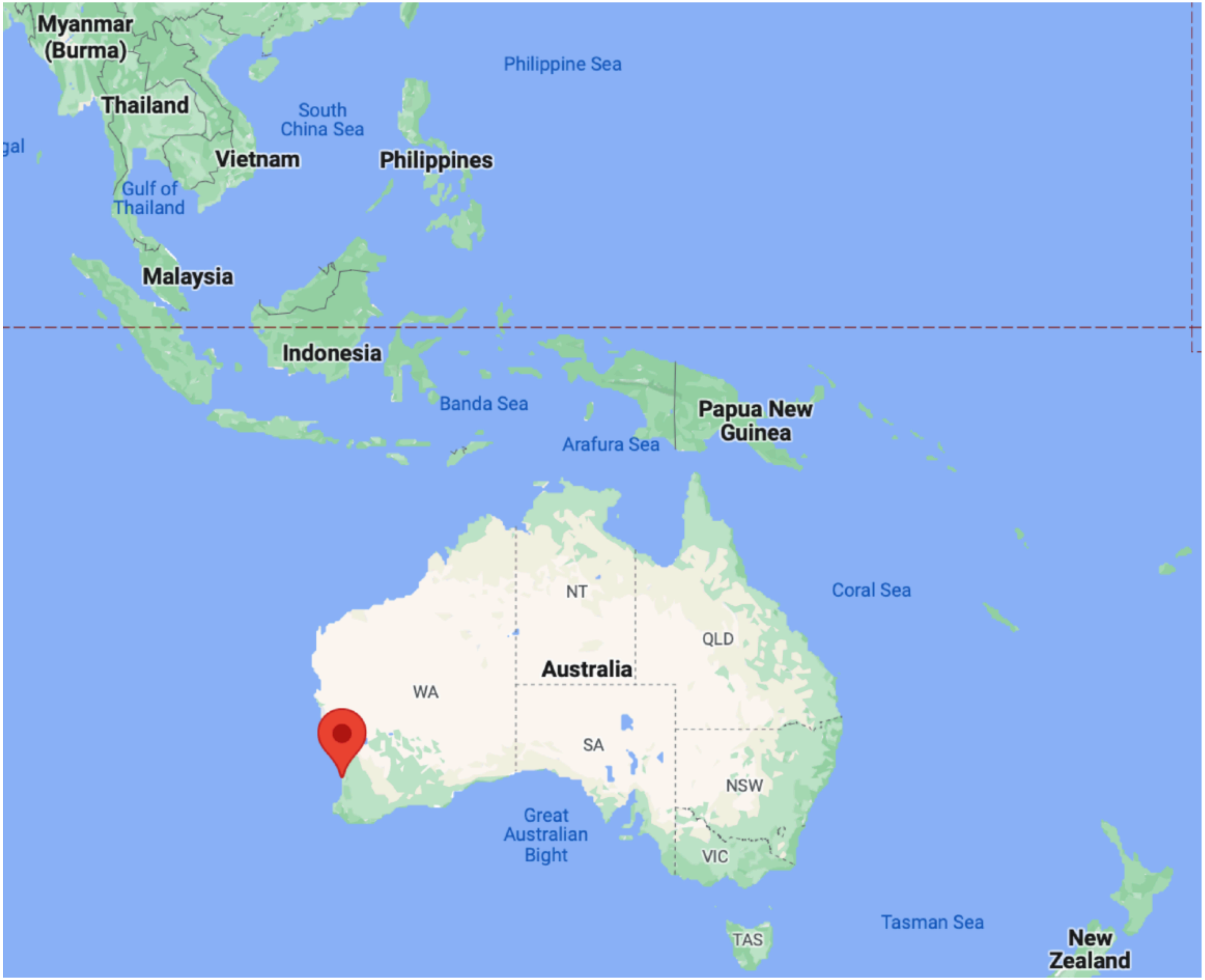
Simple Coordinates Conversion: (Alt, Az) of NCP and SCP

- The altitude and azimuth of stars depend on its coordinates on the celestial sphere (RA & Dec), your latitude, and the local *sidereal* time
- For example, from the diagram below, you can see that the altitude of the NCP (close to Polaris) equals the latitude and its Azimuth is always 0 deg.



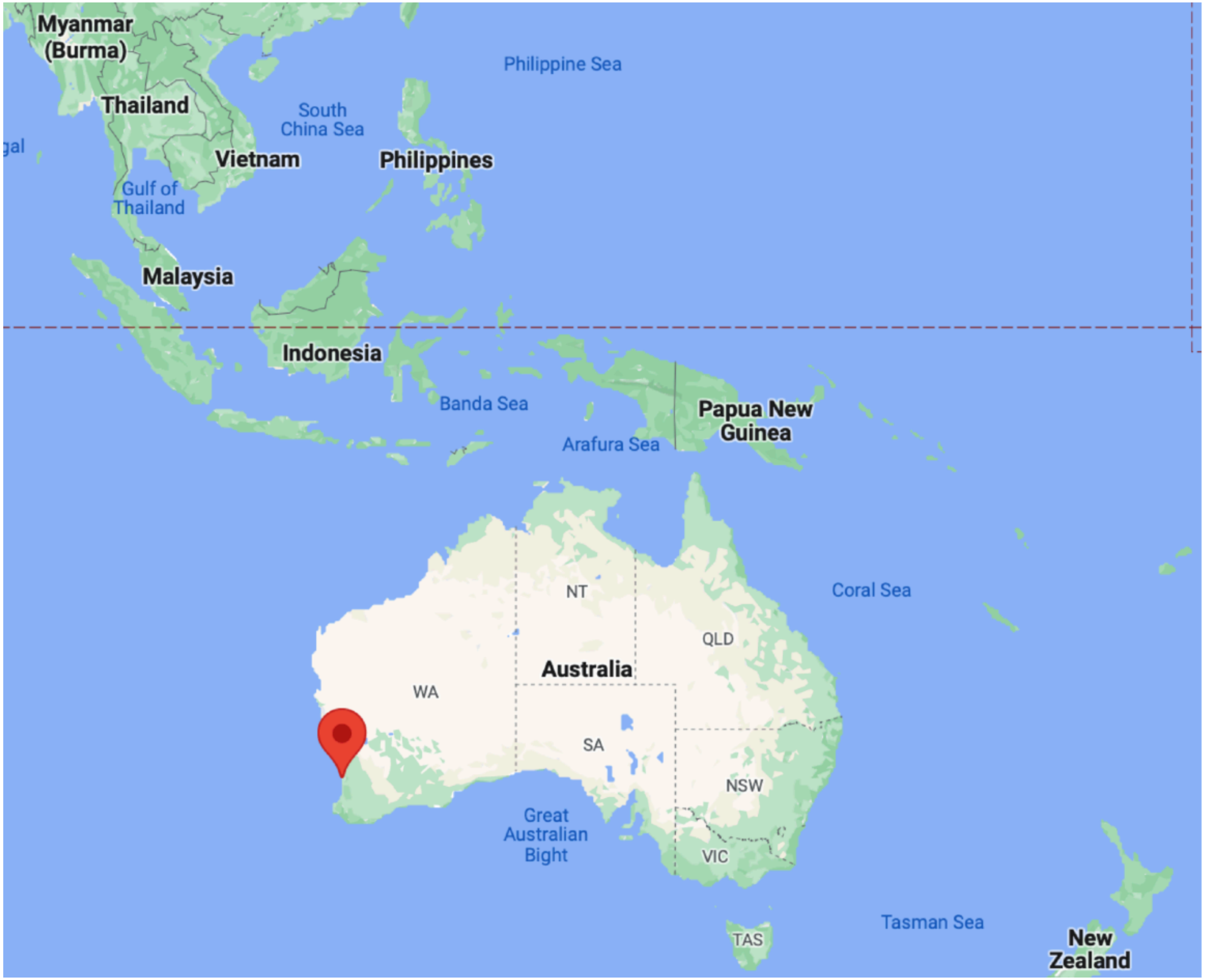


Perth is at a latitude of 32° S. (RA, Dec) of SCP = (Undefined, -90d)
What is the altitude and azimuth of the **south** celestial pole (SCP)?



Perth is at a latitude of 32° S.

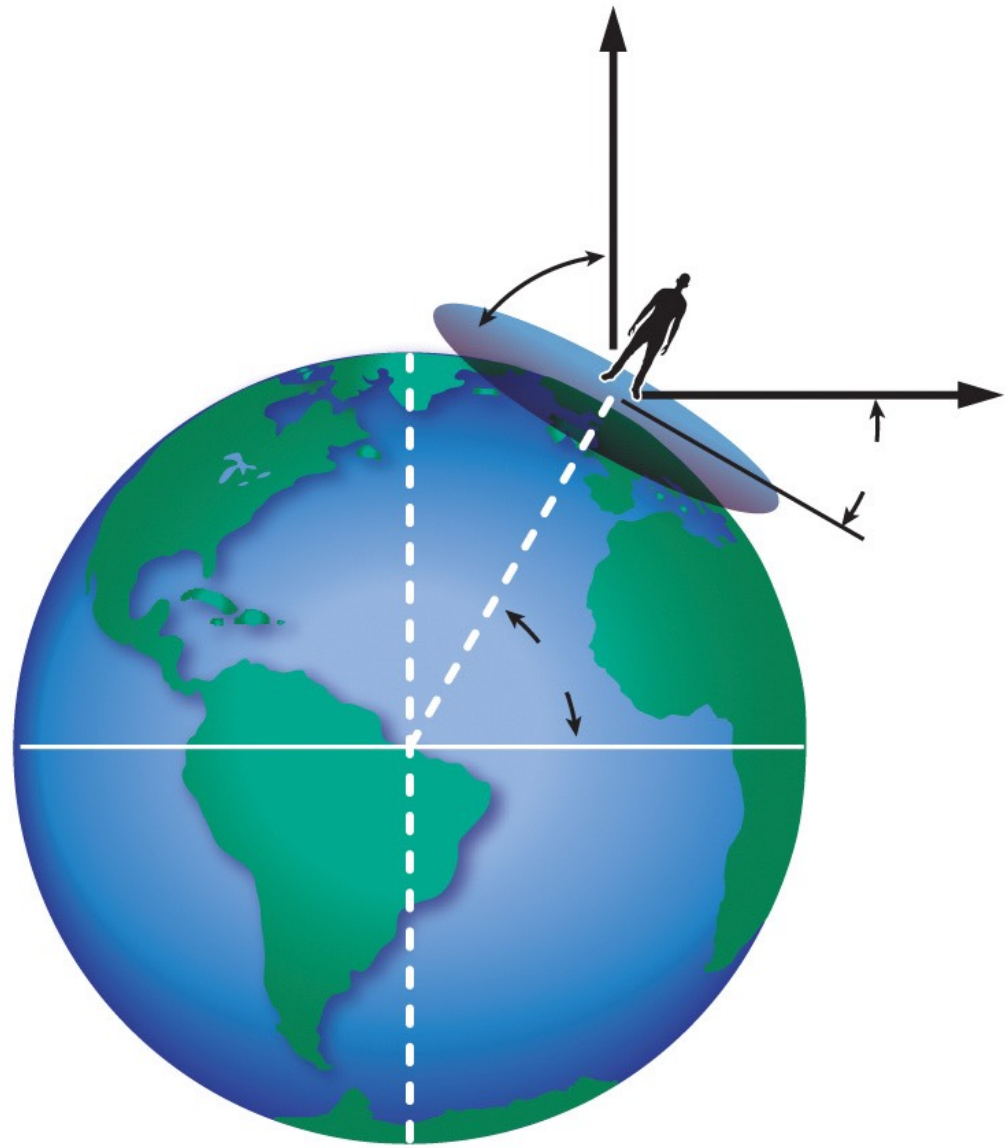
What is the altitude and azimuth of the **NCP**?

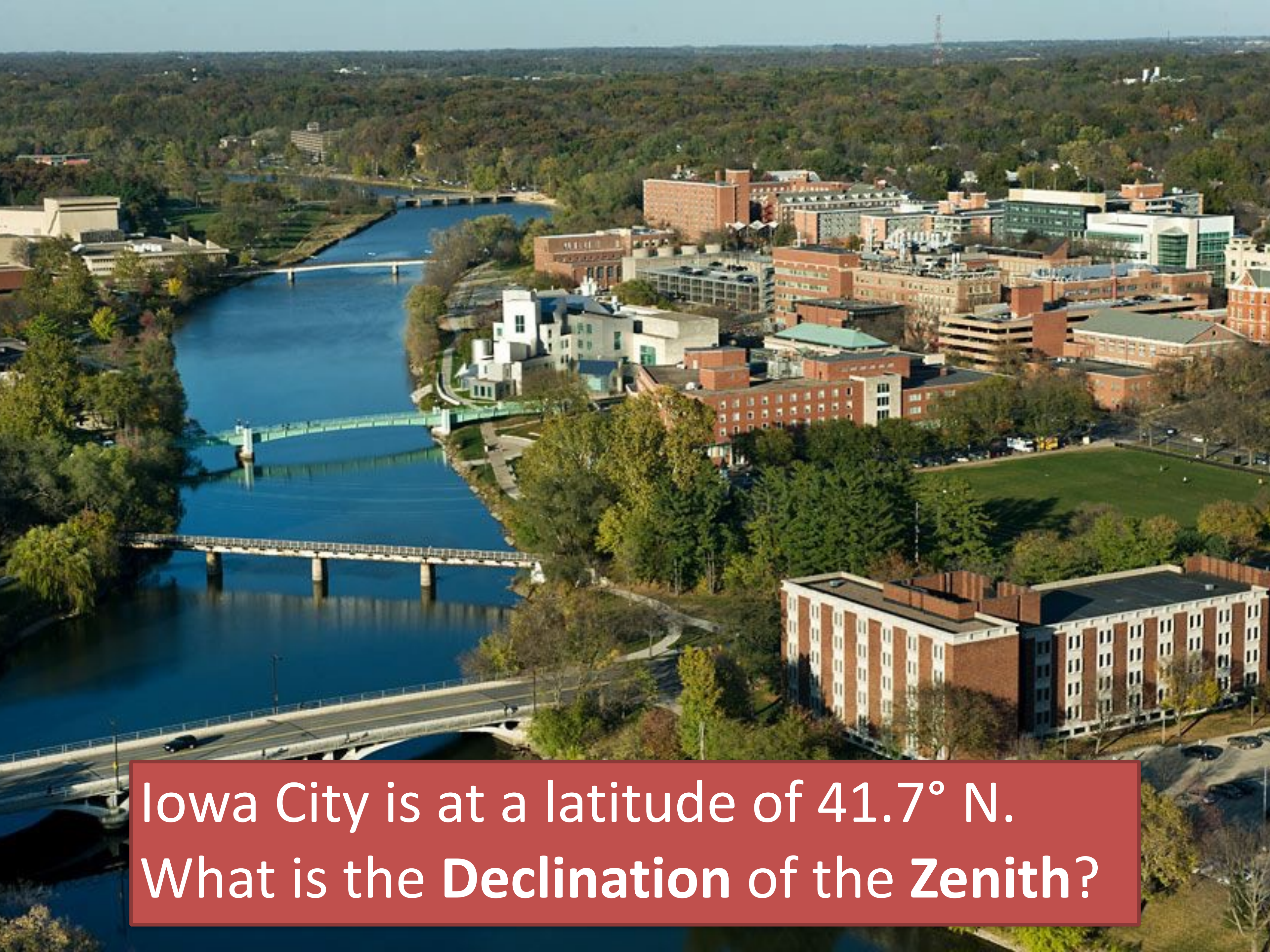


Simple Coordinates Conversion: (RA, Dec) of Zenith

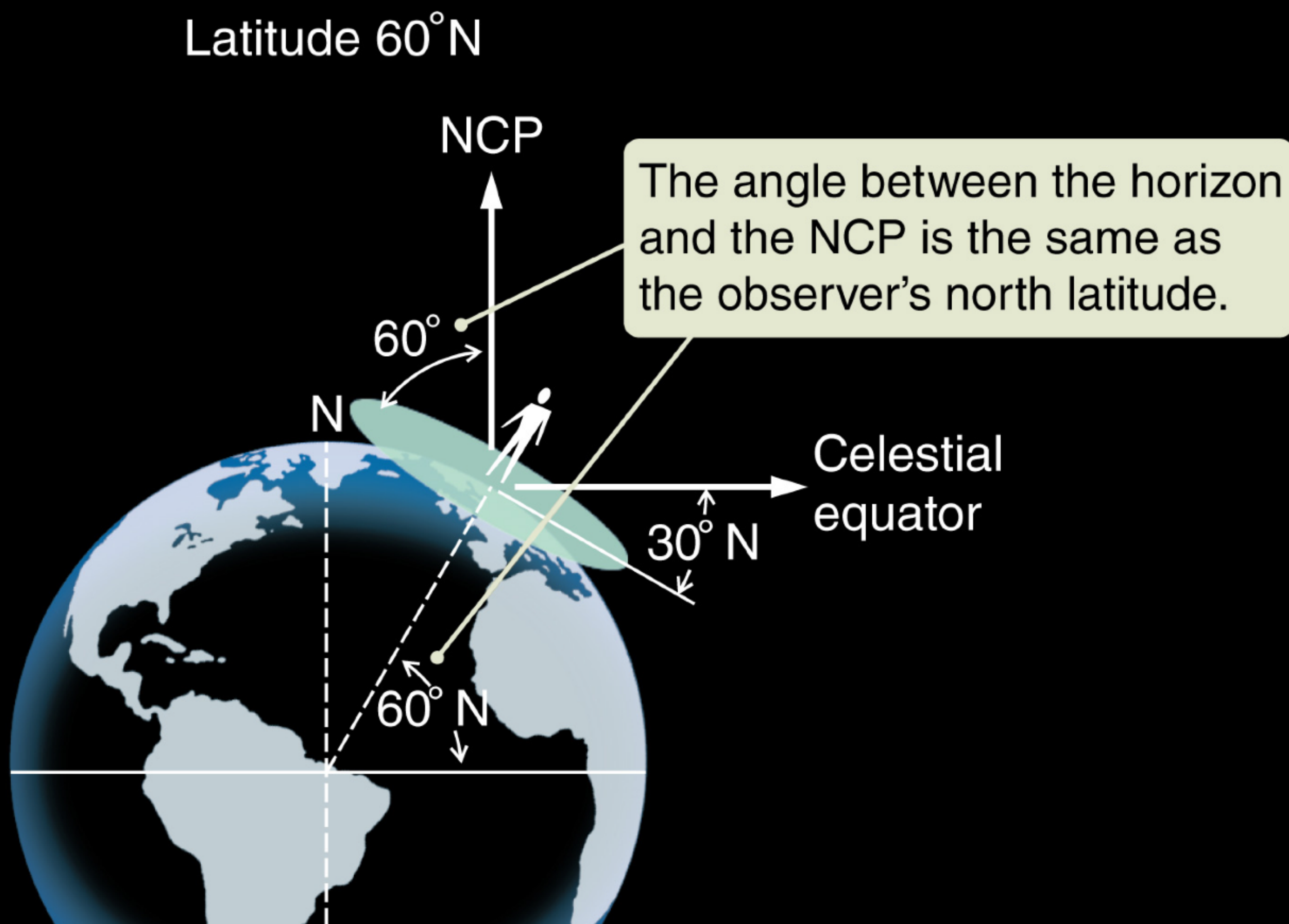
The RA & Dec of Local Zenith

- (Alt, Az) of local Zenith = (90 deg, 0 deg)
- What is the Declination of a star at Zenith?
- What is the Right Ascension of a star at Zenith?





Iowa City is at a latitude of 41.7° N.
What is the **Declination** of the **Zenith**?



Iowa City is at a latitude of 41.7° N.
What is the **Declination** of the **Zenith**?

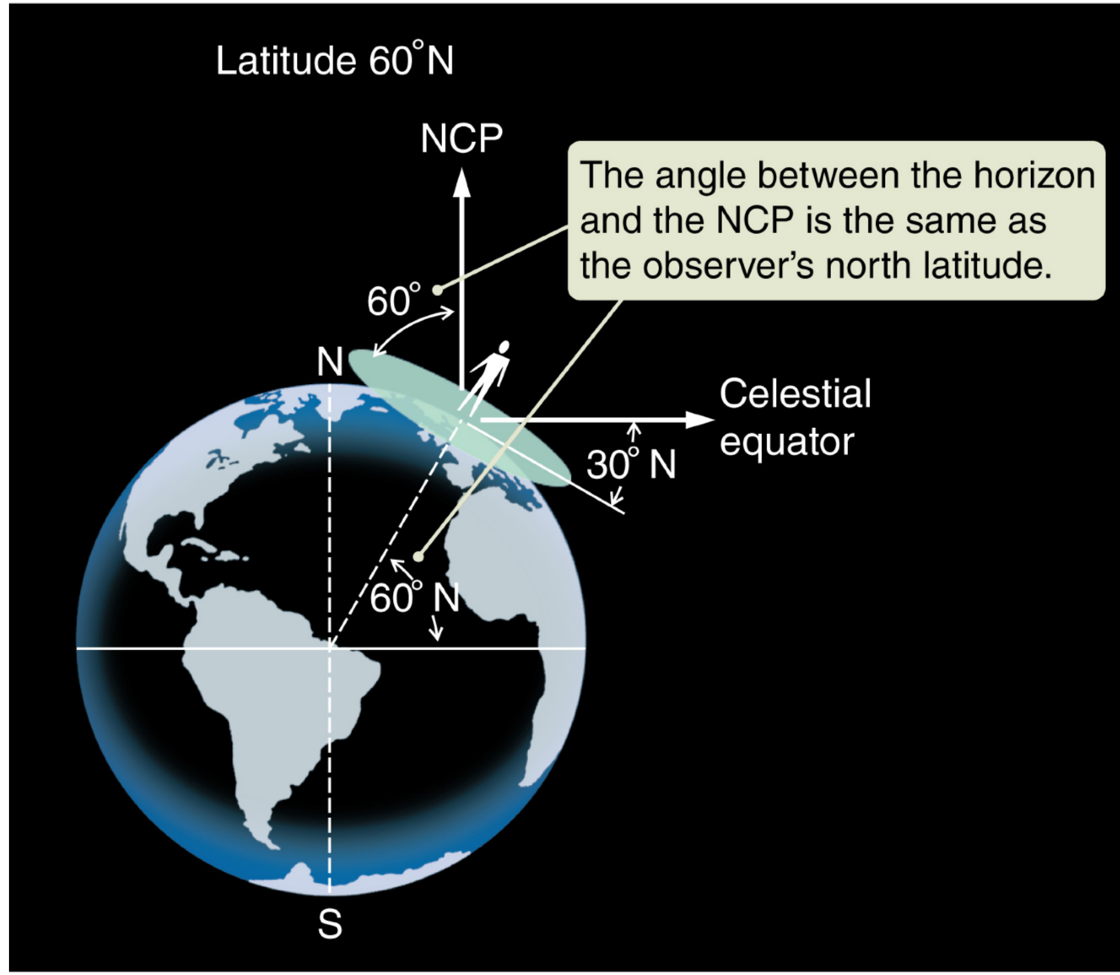
Vega = alpha Lyra

RA: 18h36m
Dec: +38d47’

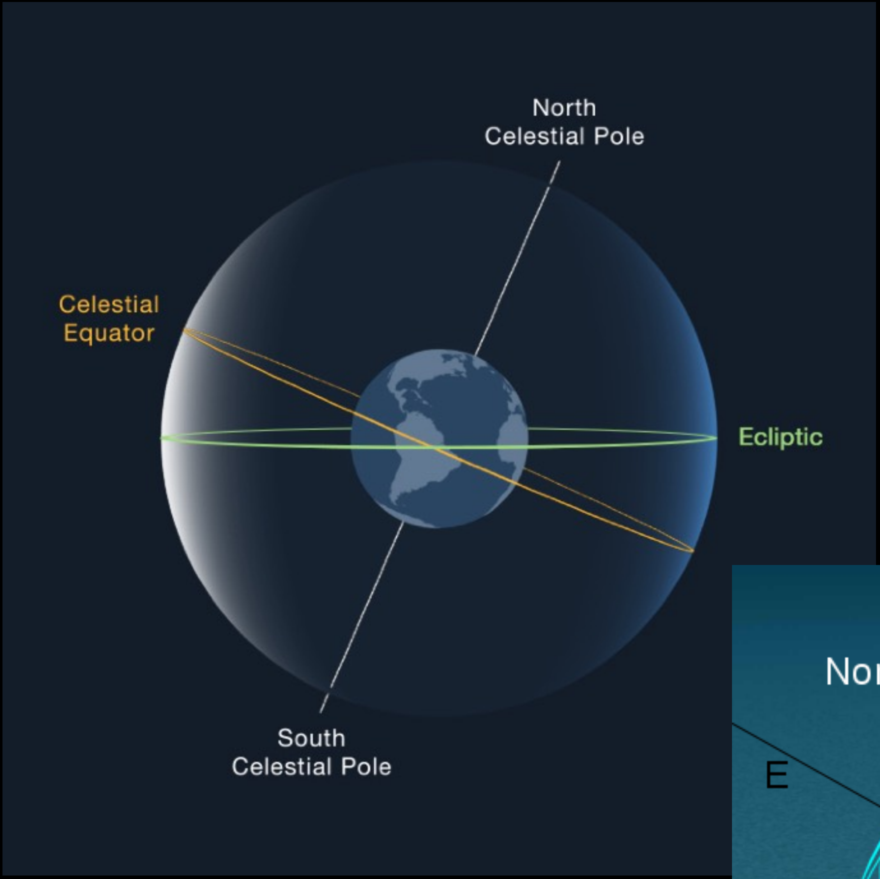
Constellation:
Lyra

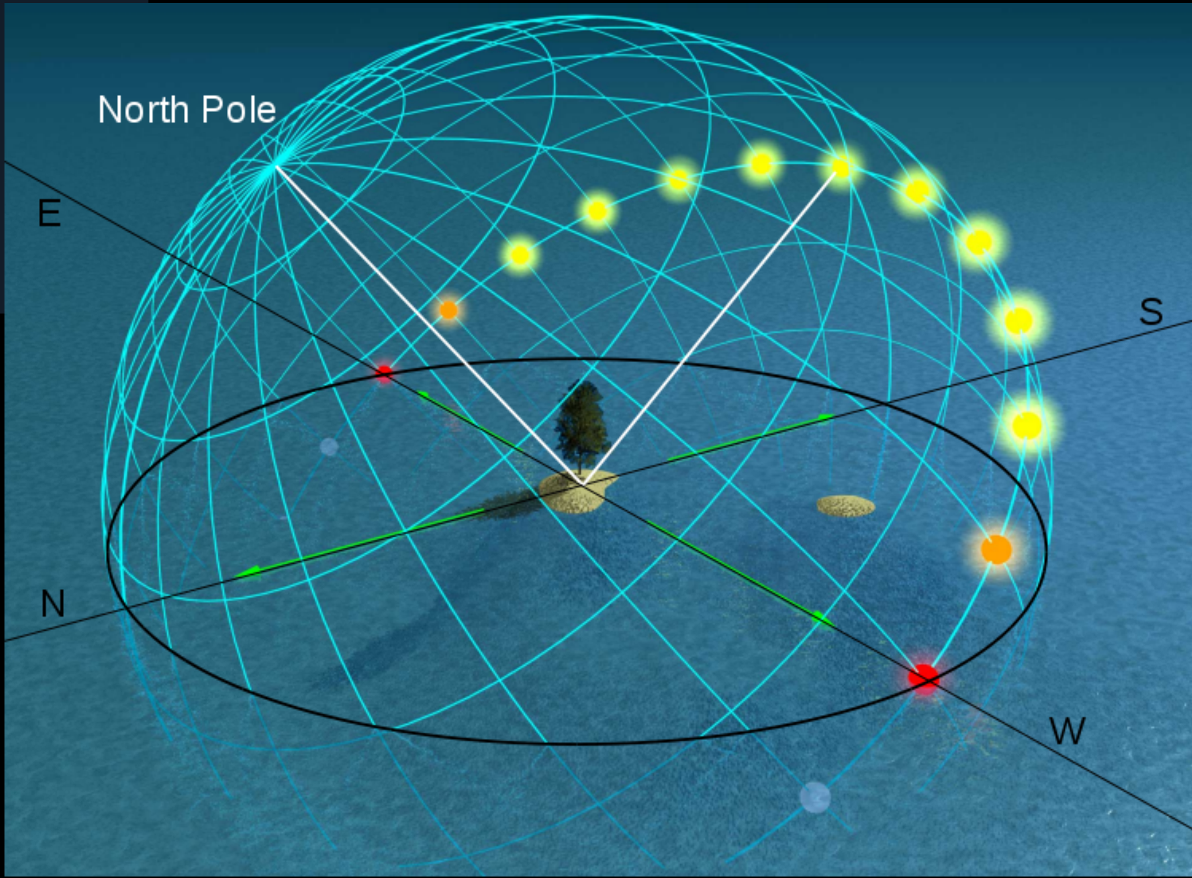
Practice: Estimate the altitude of Pleiades

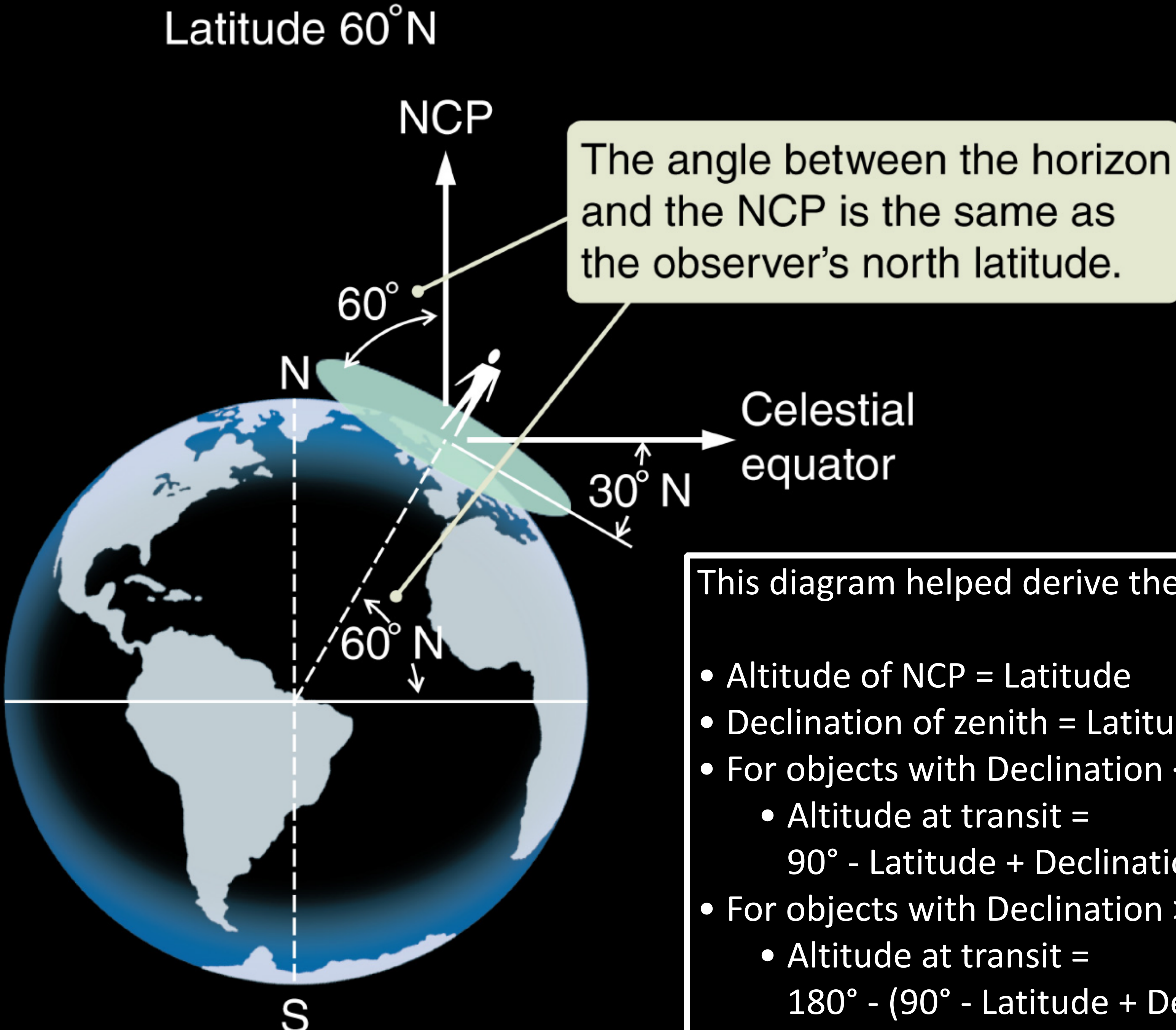
- Pleiades cluster (M45) RA 3h47m, Dec +24.1°
- Iowa City coordinates Long = 91.5° W, Lat = 41.6° N
- At LST = 03:47, estimate the Altitude of Pleiades



Coordinate Systems: Summary







This diagram helped derive the equations:

- Altitude of NCP = Latitude
- Declination of zenith = Latitude
- For objects with Declination < Latitude
    - Altitude at transit = 90° - Latitude + Declination
- For objects with Declination > Latitude
    - Altitude at transit = 180° - (90° - Latitude + Declination)

Full Coordinate Transformation Formulae: From (RA, Dec) to (Alt, Az)

- RA, Dec, Alt, Az, LST, HA, Latitude =
  $\alpha, \delta, a, A_z, t, h, \phi$
- (a, A_z) varies with time, so we first convert the object's RA (α) to HA (h) at LST (t):
  $h = (t - \alpha) \times 15°/\text{hr} = (t - \alpha)/12\ \text{hr} \times \pi\ \text{rad}$
- Next, with spherical trigonometry, we can derive:
  $\sin a = \sin\phi \sin\delta + \cos\phi \cos\delta \cos h$
  $\tan A_z = \sin h / (\cos h \sin\phi - \tan\delta \cos\phi)$
- Sanity check:
  calculate (a, A_z) for $h = 0$, i.e., transit the meridian

Self-test Questions for Coordinate Systems

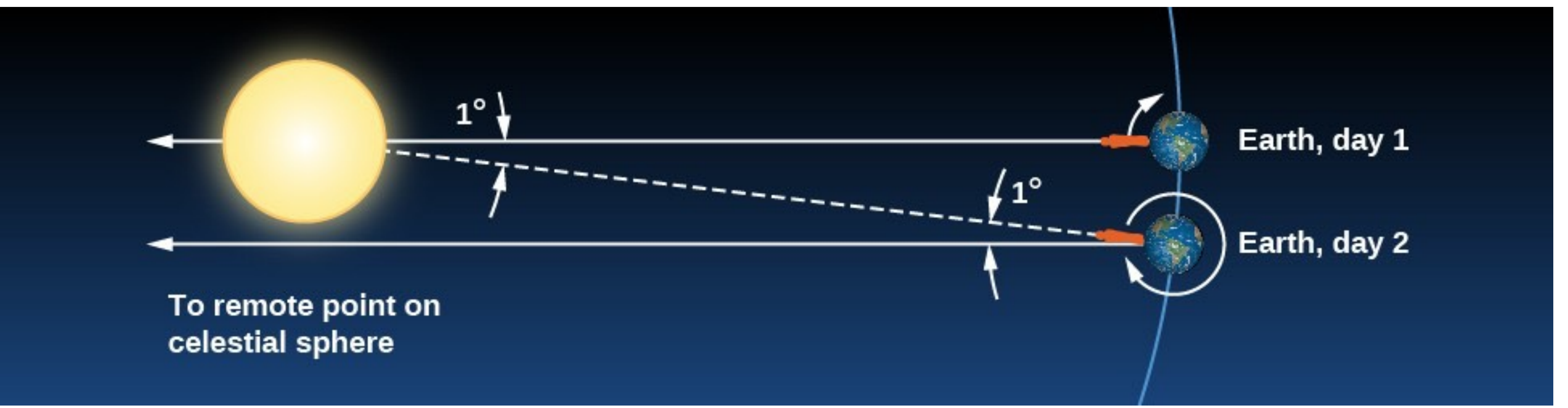
- Definitions & Diagrams:
  - NP+SP, Equator, Prime Meridian — (Longitude, Latitude)
  - NCP+SCP, Equator, Ecliptic — (RA, Dec)
  - Horizon, Zenith, Meridian — (Alt, Az)
- Simple Coordinate Transformation (at a given location):
  - Calculate the altitude of the Sun at noon on a given date (e.g., June 20).
  - Calculate the altitude of a star (e.g., Rigel) when it transits the meridian.
  - Calculate the declination of a star for which you have measured the altitude when it transits the meridian.
- Navigation Part I: Latitude measurements
  - Describe at least two astronomical methods; List the tools needed
- Calendar and Date
  - How would you determine the length of a year?
  - How would you determine the length of a day?

SOLAR DAY VS. SIDEREAL DAY

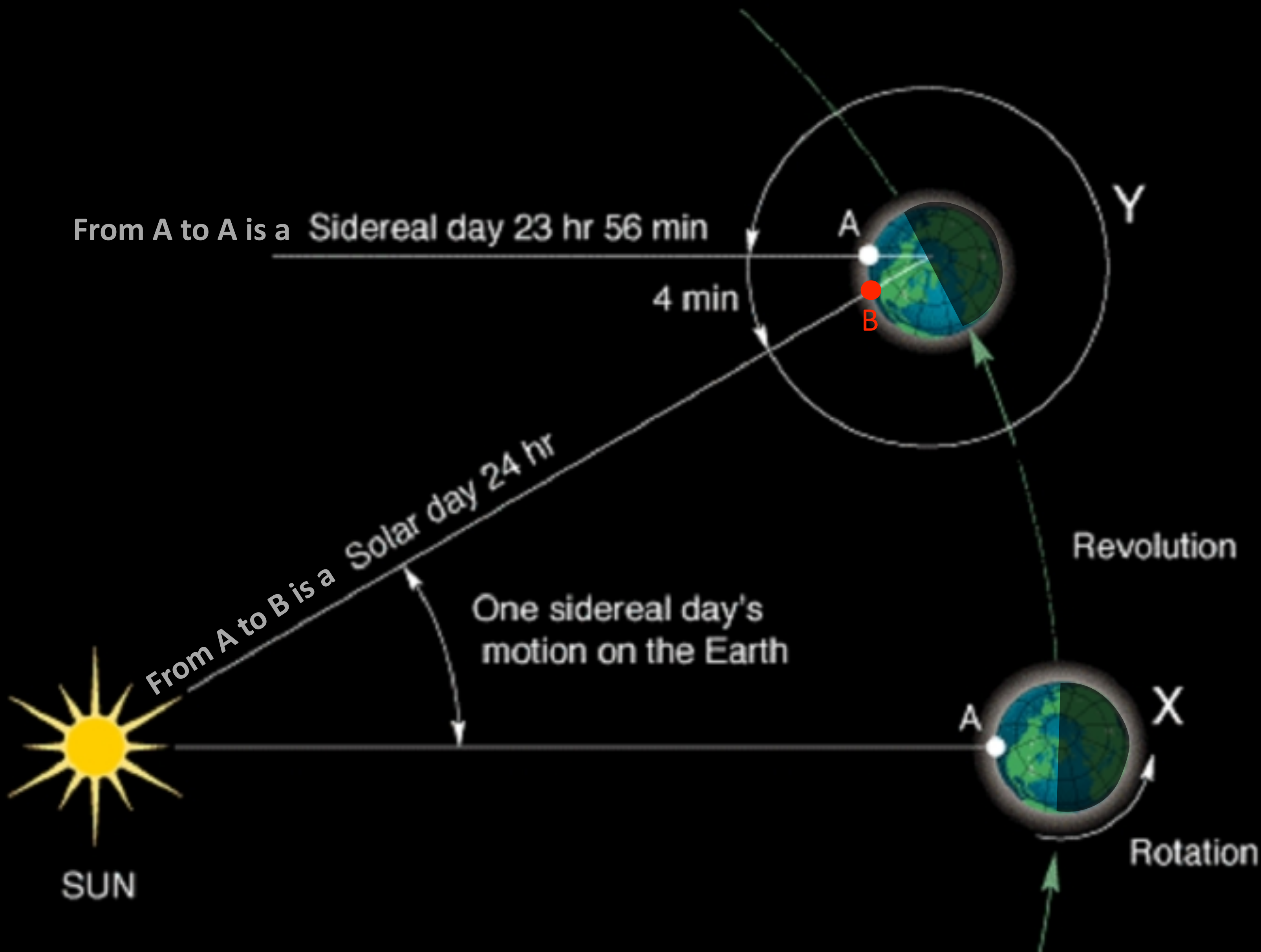
Why are there two different days?

Solar Day vs. Sidereal Day

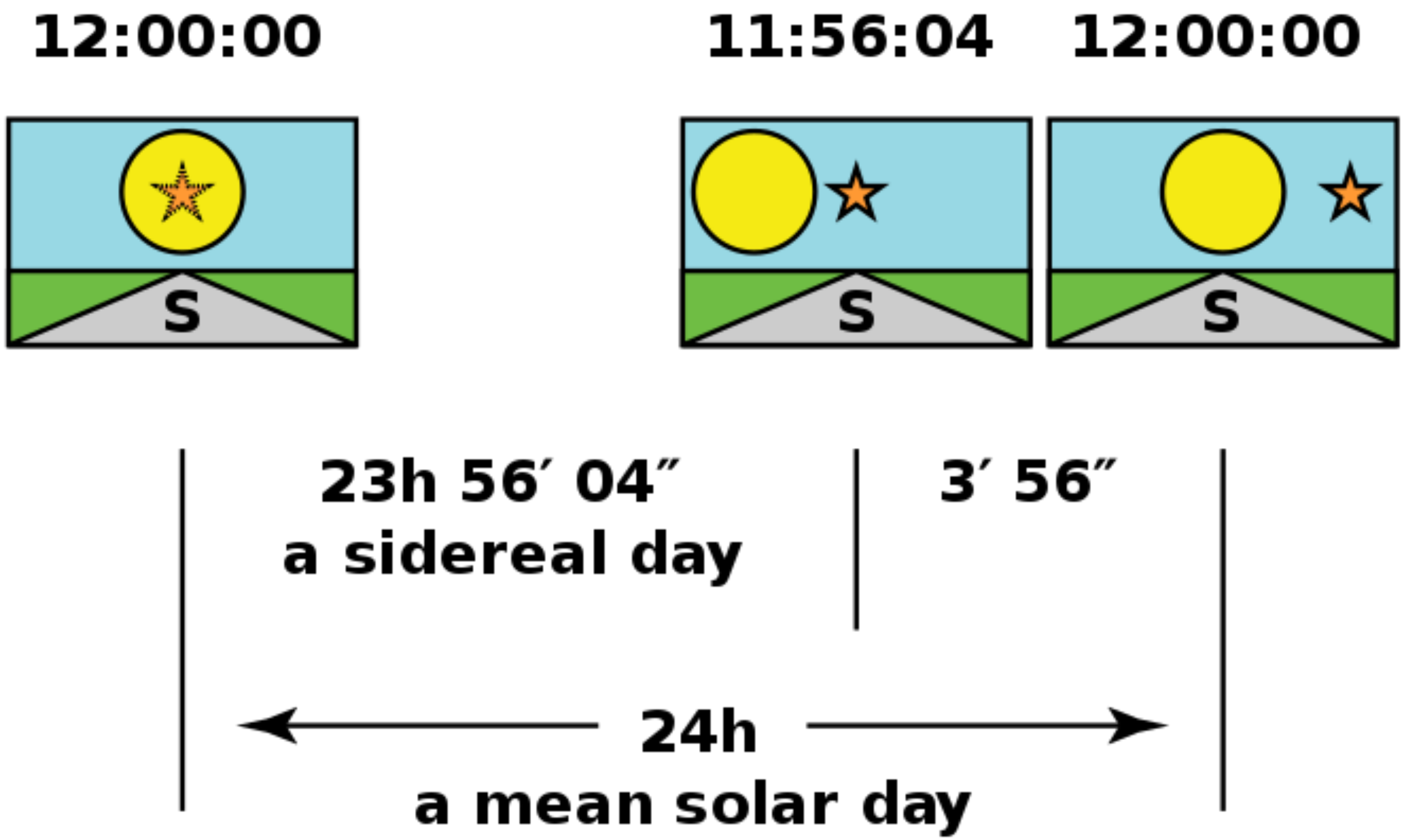
- A **(Mean)** Solar Day = the time interval between two consecutive noons **(averaged over a year)**
- A Sidereal Day = the time interval between two consecutive transits of a distant star



Sidereal Day vs. Solar Day

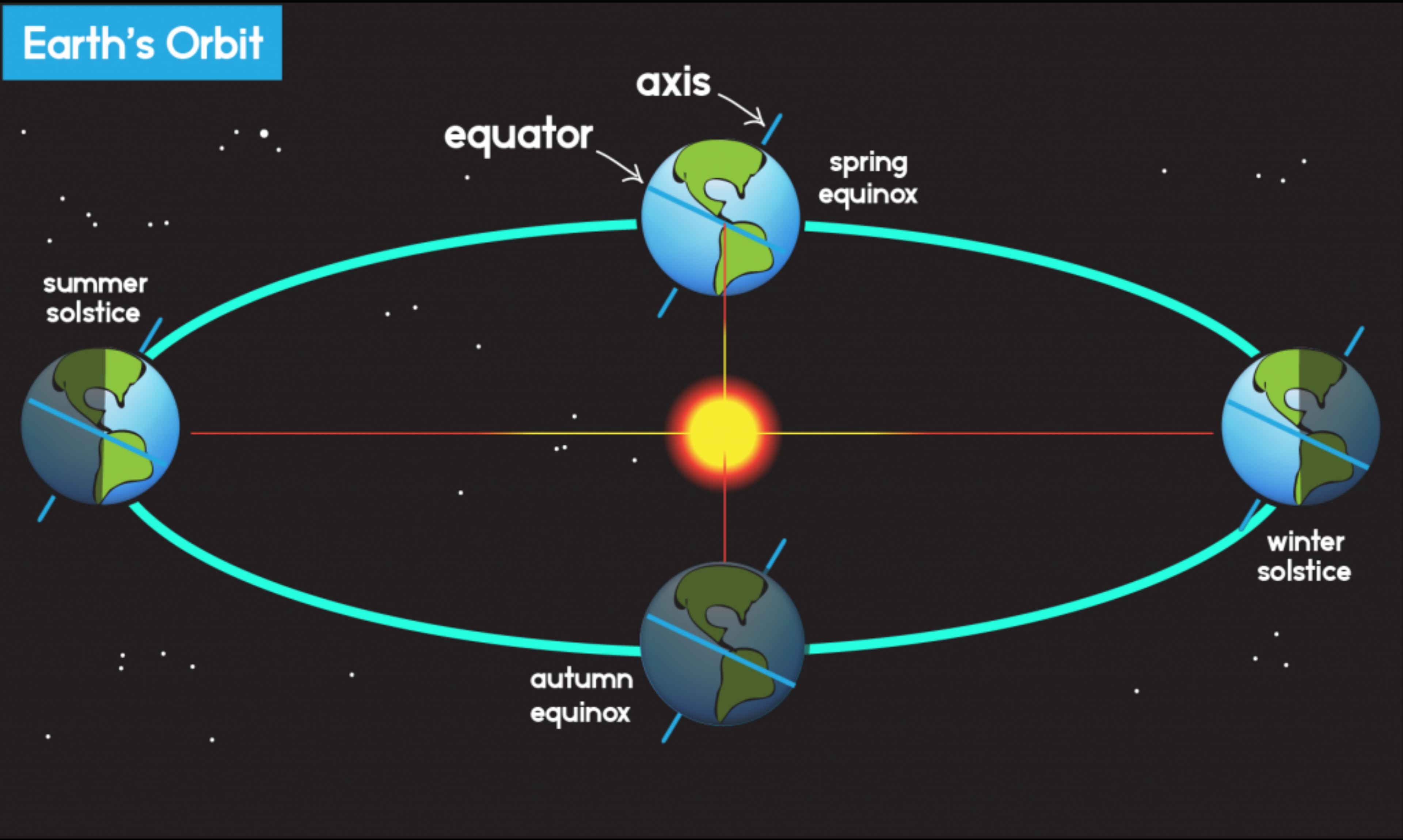


Solar Day vs. Sidereal Day

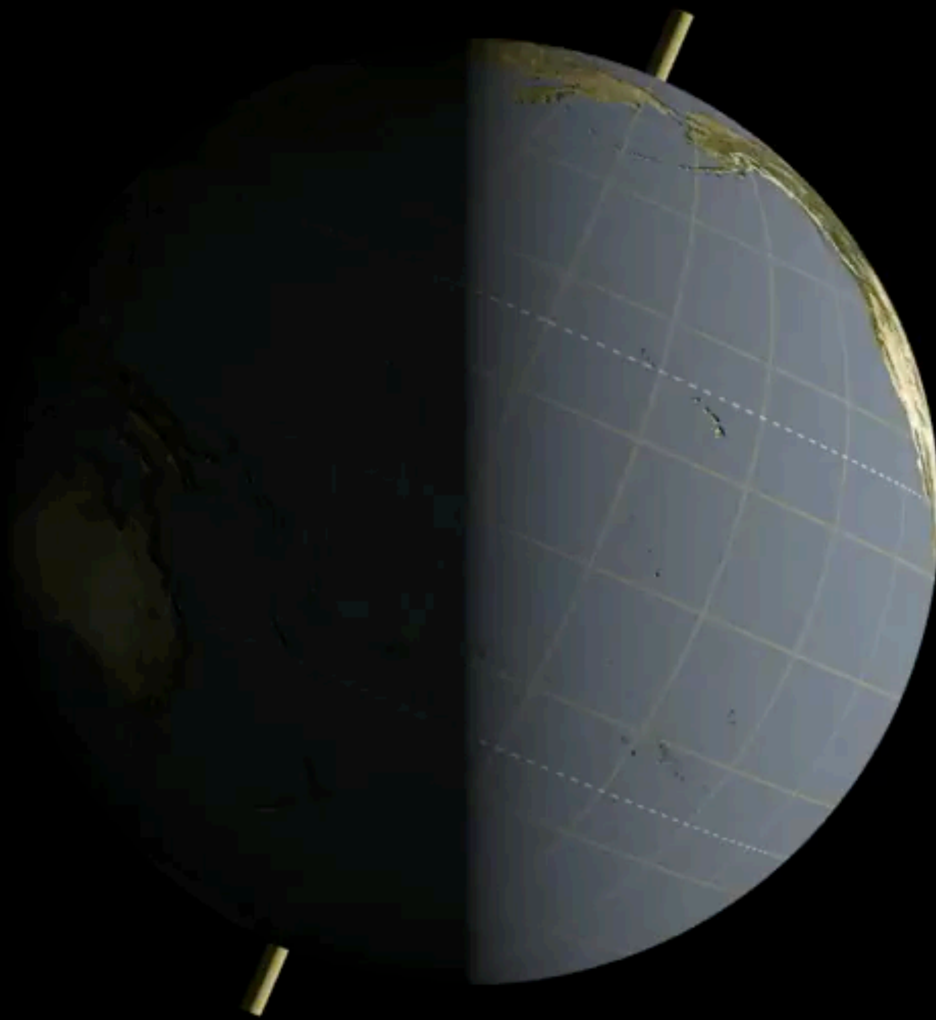


Motions of the Earth and Obliquity:

The Causes of Earth's Seasons

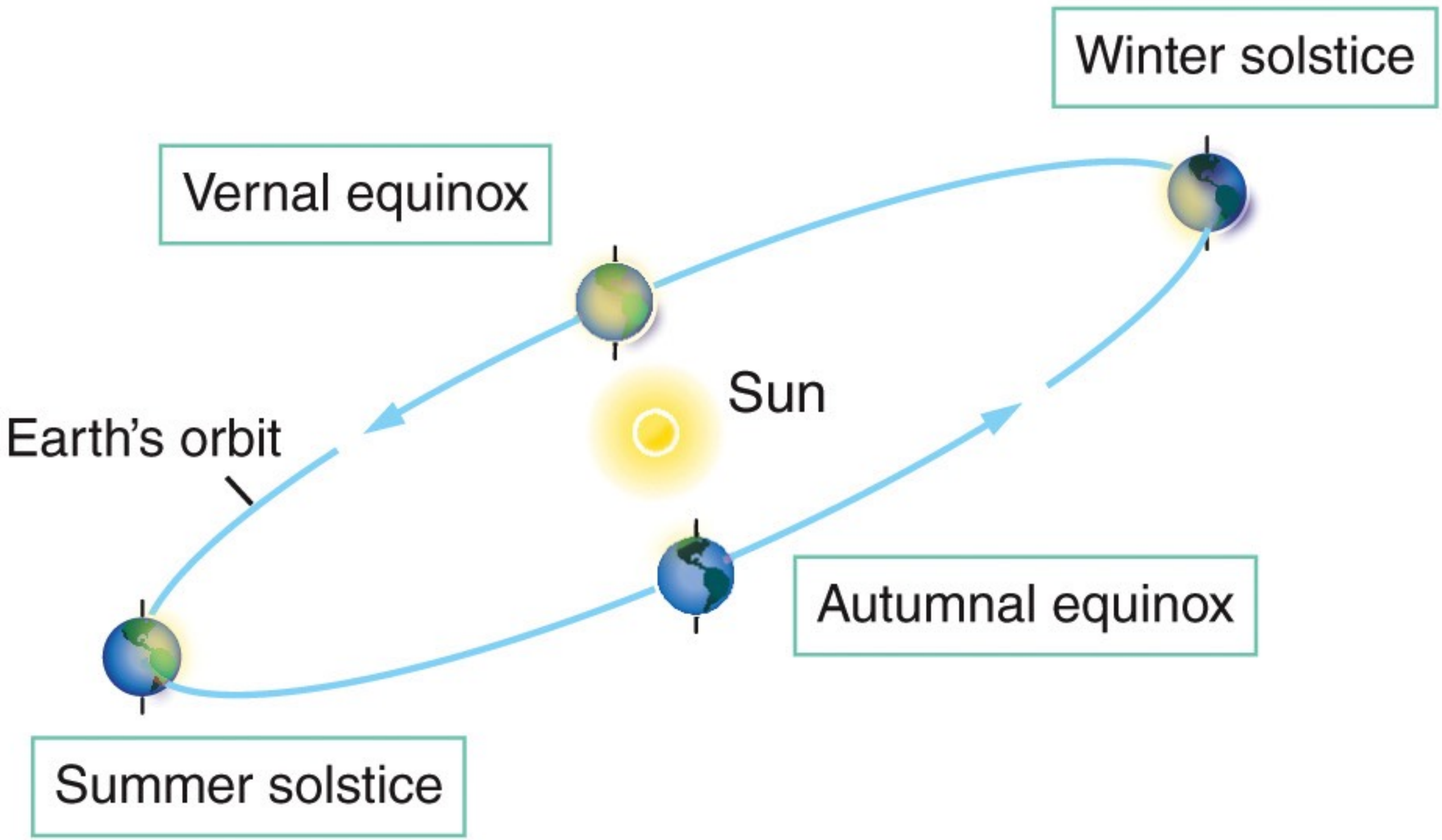


Daily Rotation: The Earth spins around its poles every sidereal day (23h56m), causing diurnal motions of objects in the sky

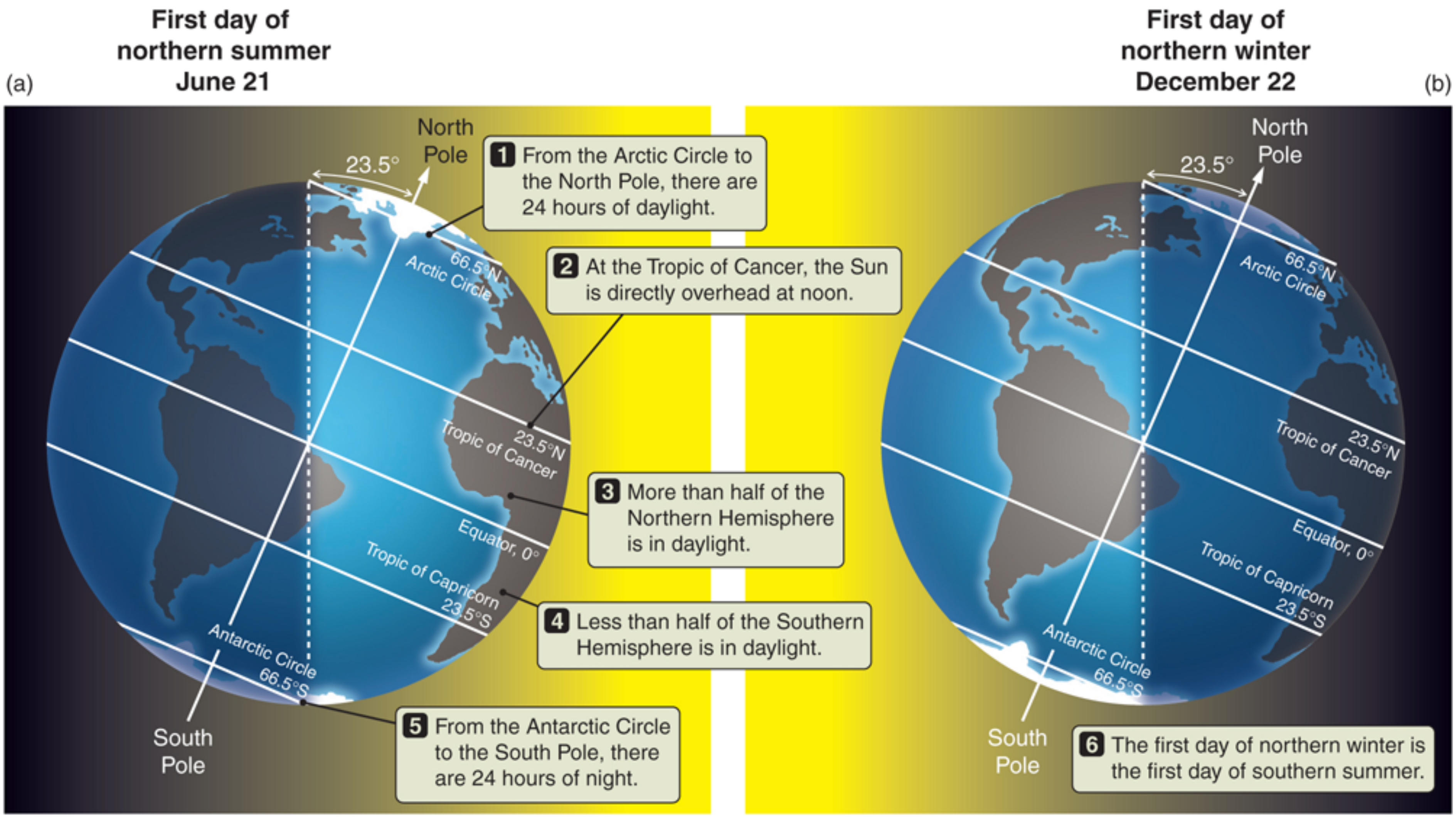


Spin of the Earth, animated for Summer Solstice (around June 20)

Yearly Revolution: Earth orbits around the Sun every year (365.2422 days), causing the 4-minute longer solar day (24h) and the annual motion of the Sun along the ecliptic



Obliquity: Earth's spin axis is tilted from the pole of the ecliptic by 23.5 degrees, causing Earth's seasons



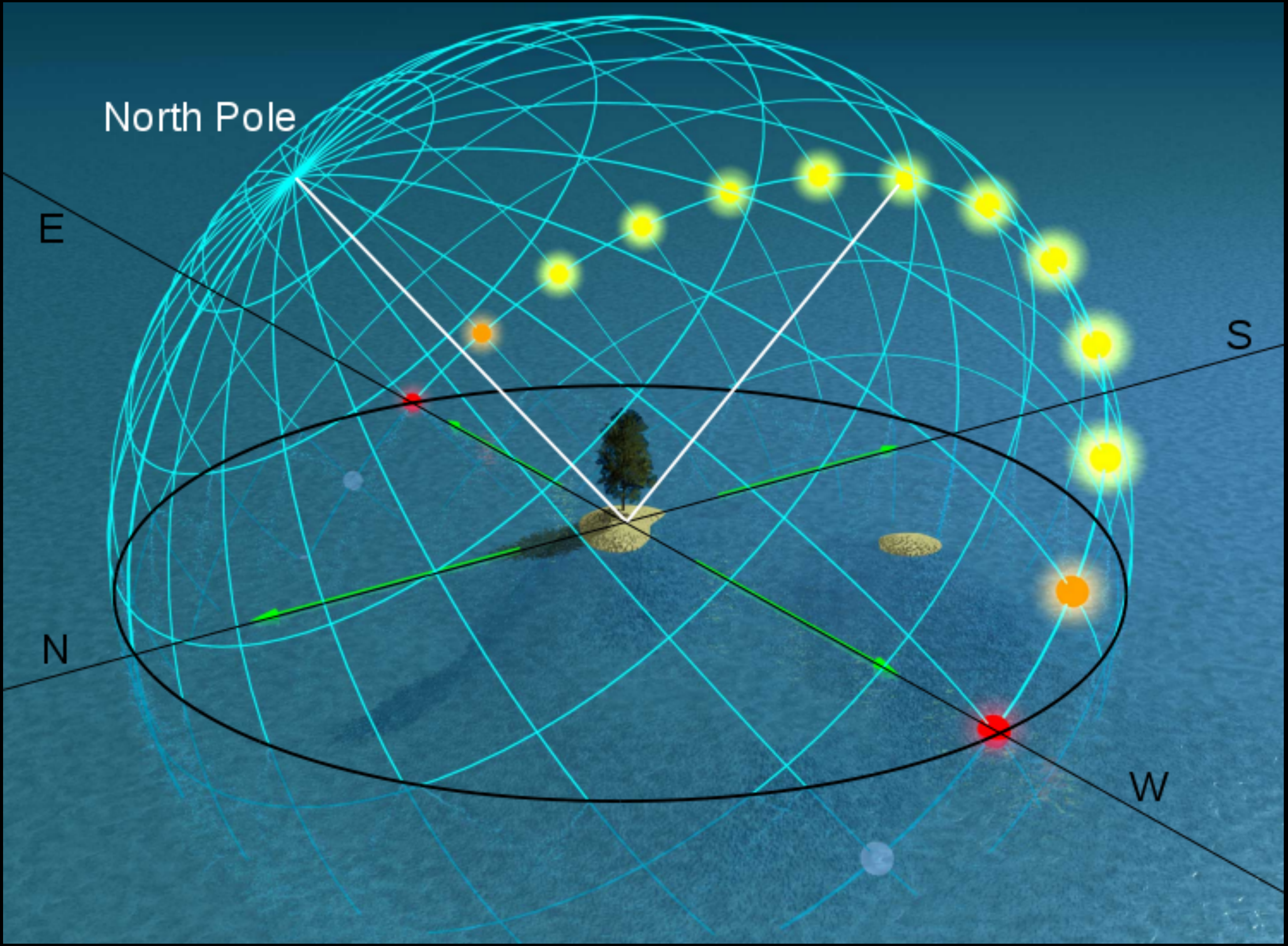
The combination of Earth's orbit and its obliquity results in the ephemeris of the Sun below

How will the ephemeris change if the obliquity changes from 23.5 degrees to 5 degrees?

	RA	Dec	Notes
Spring Equinox (Mar 20)	***0 hr***	***0 deg***	***Origin of Celestial sphere: aka, vernal equinox***
Summer Solstice (Jun 21)	***6 hr***	***+23.5 deg***	***longest day in a year***
Fall Equinox (Sep 22)	***12 hr***	***0 deg***	***equal day and night, same as Spring Equinox***
Winter Solstice (Dec 21)	***18 hr***	***-23.5 deg***	***longest night in a year***

Season Factor I: The length of daytime increases with the Sun's declination

The Sun stays above the horizon longer as its declination increases



Season Factor II:
The altitude of the Sun at noon increases with the Sun's Declination

The Solar Analemma

over

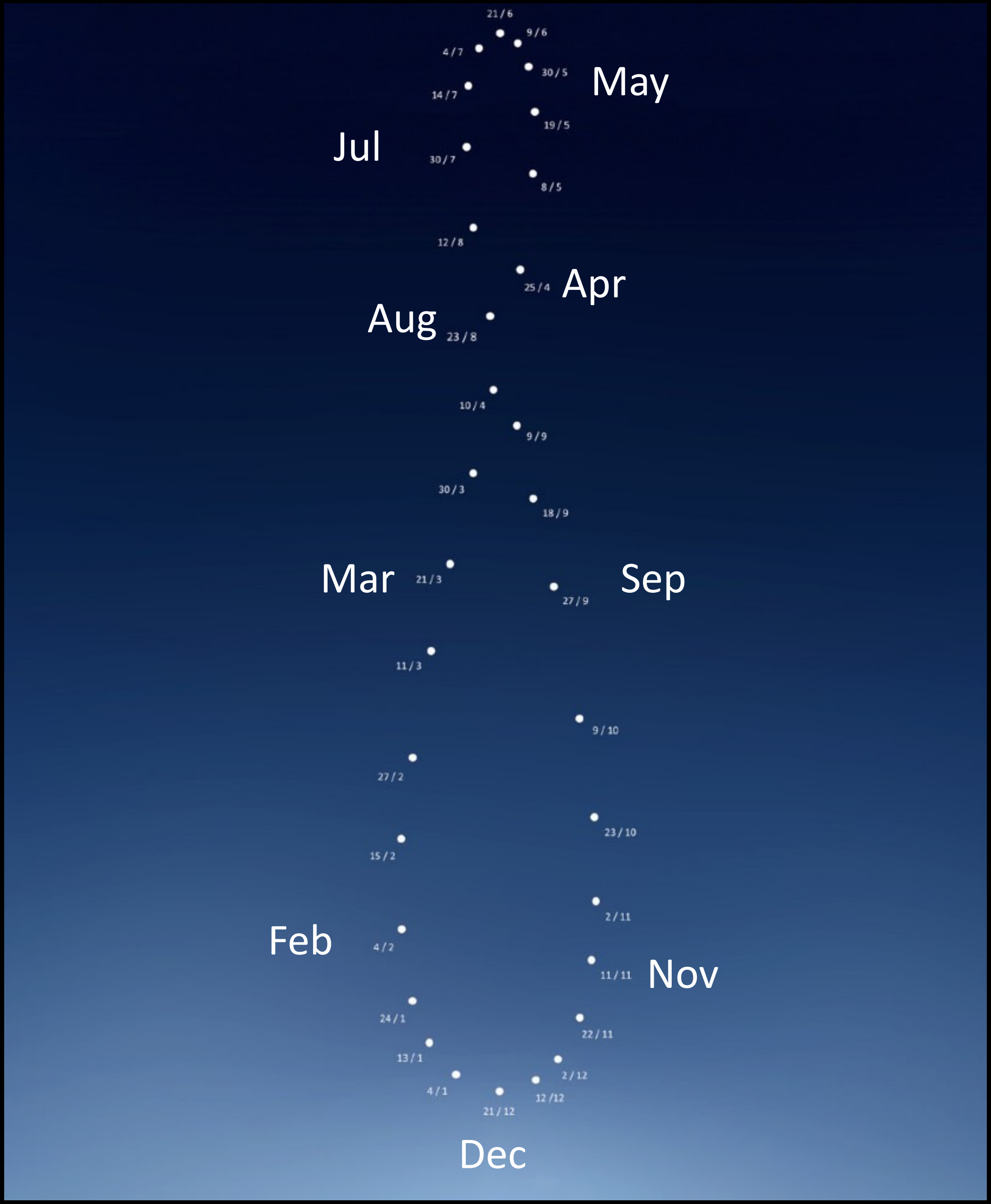
Edmonton, AB

June 21, 2013 - June 2, 2014

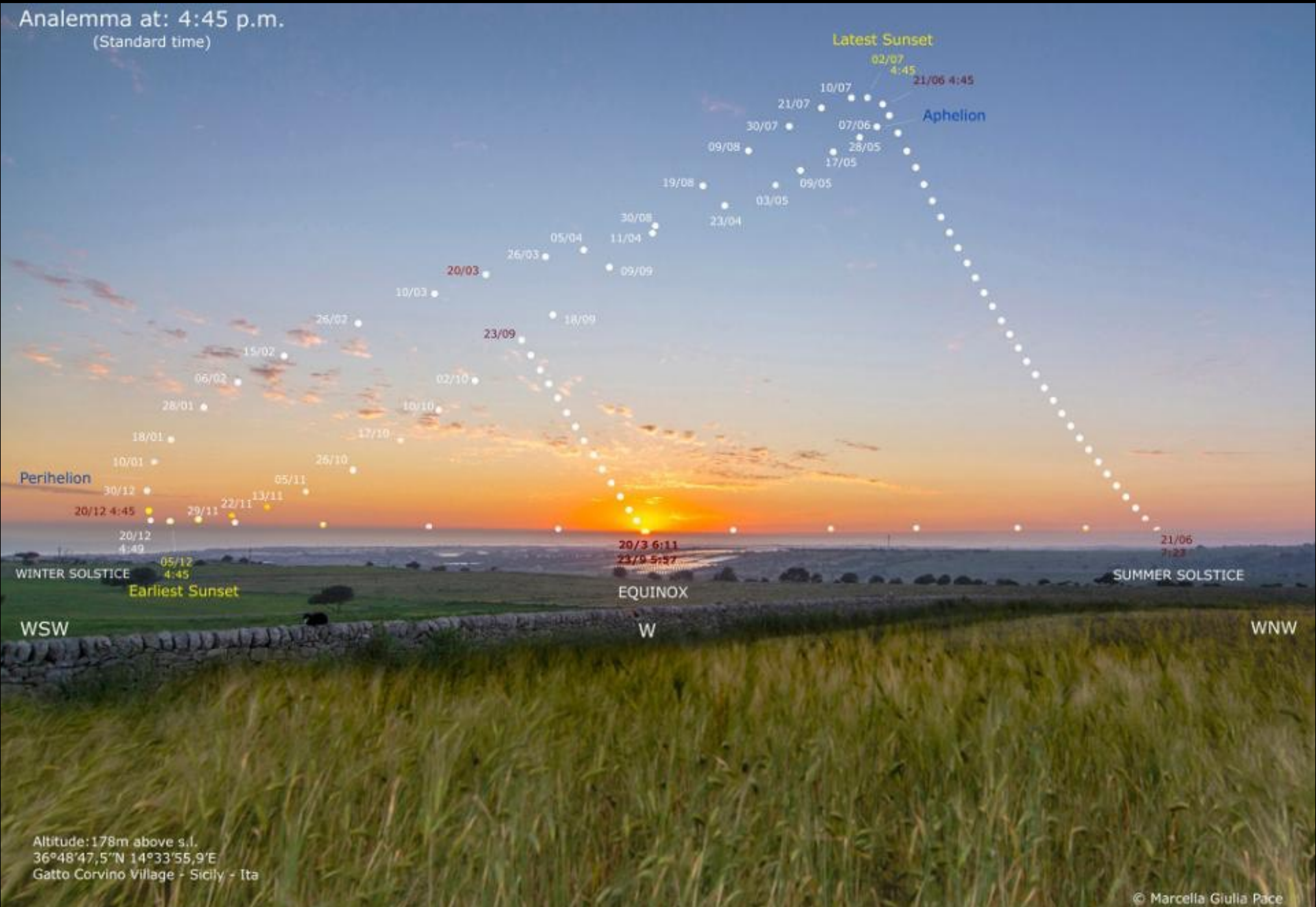
09:45 MT

Solar analemma from Sulmona, Italy

A compilation of images of the Sun taken at the same time (12pm) every ten days and at the same place



altitude of Sun at noon = (90 deg - latitude) + declination of Sun


Analemma at: 4:45 p.m.
(Standard time)
Latest Sunset
02/07
4:45
21/06 4:45
10/07
21/07
Aphelion
30/07
07/06
28/05
09/08
17/05
19/08
09/05
03/05
23/04
30/08
05/04
11/04
26/03
20/03
09/09
10/03
26/02
18/09
23/09
15/02
06/02
02/10
28/01
10/10
18/01
17/10
10/01
26/10
Perihelion
05/11
30/12
13/11
20/12 4:45
29/11
22/11
20/12
4:49
05/12
4:45
20/3 6:11
23/9 5:57
21/06
7:23
WINTER SOLSTICE
Earliest Sunset
EQUINOX
SUMMER SOLSTICE
WSW
W
WNW
Altitude:178m above s.l.
36°48'47,5"N 14°33'55,9'E
Gatto Corvino Village - Sicily - Ita
© Marcella Giulia Pace

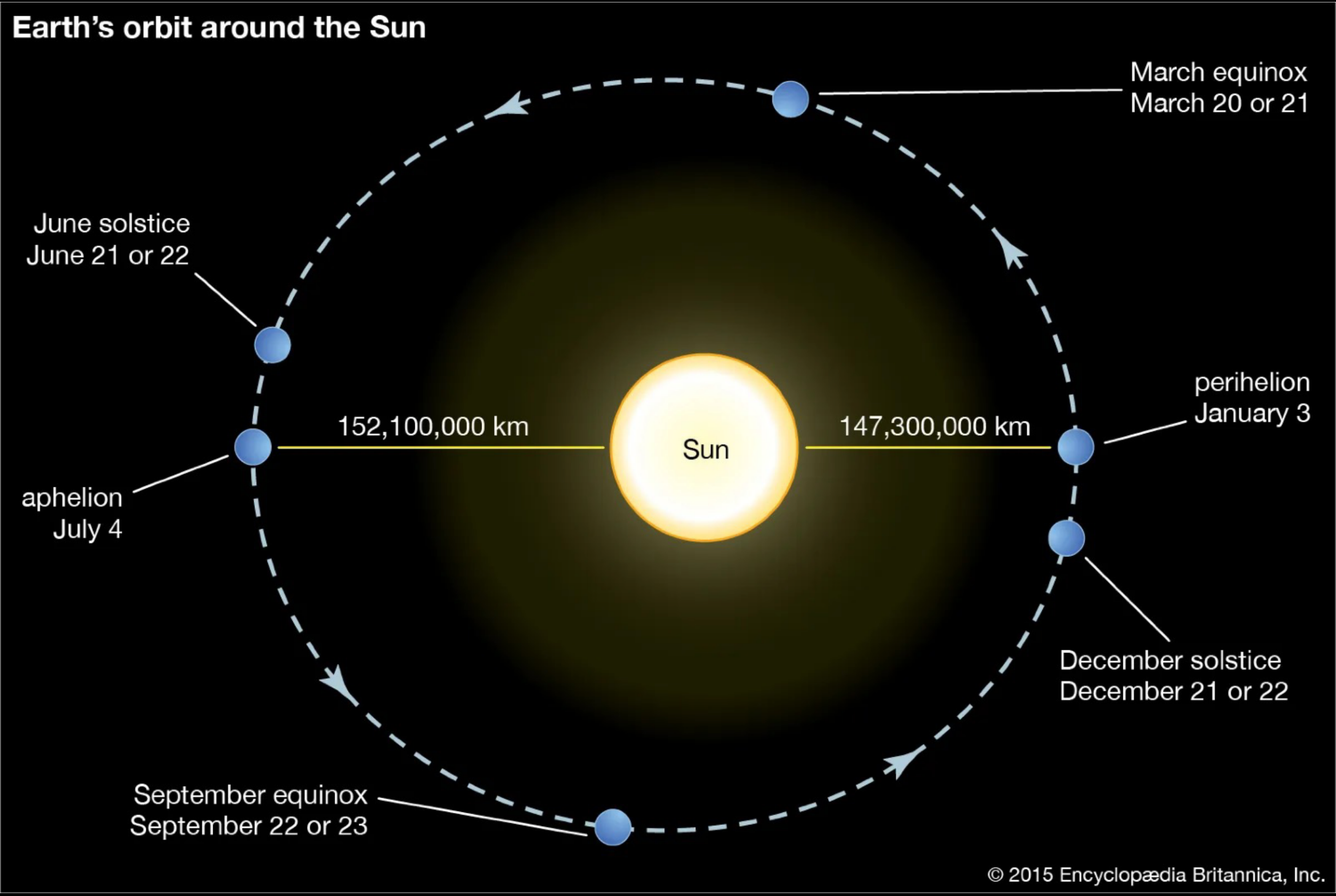
Chichen Itza - Temple of Kukulcan (800-1200 AD)

side slope = 47 deg ~ altitude of the Sun at Winter Solstice

What's the latitude of Chichen Itza?

altitude of Sun at noon = (90 deg - latitude) + declination of Sun

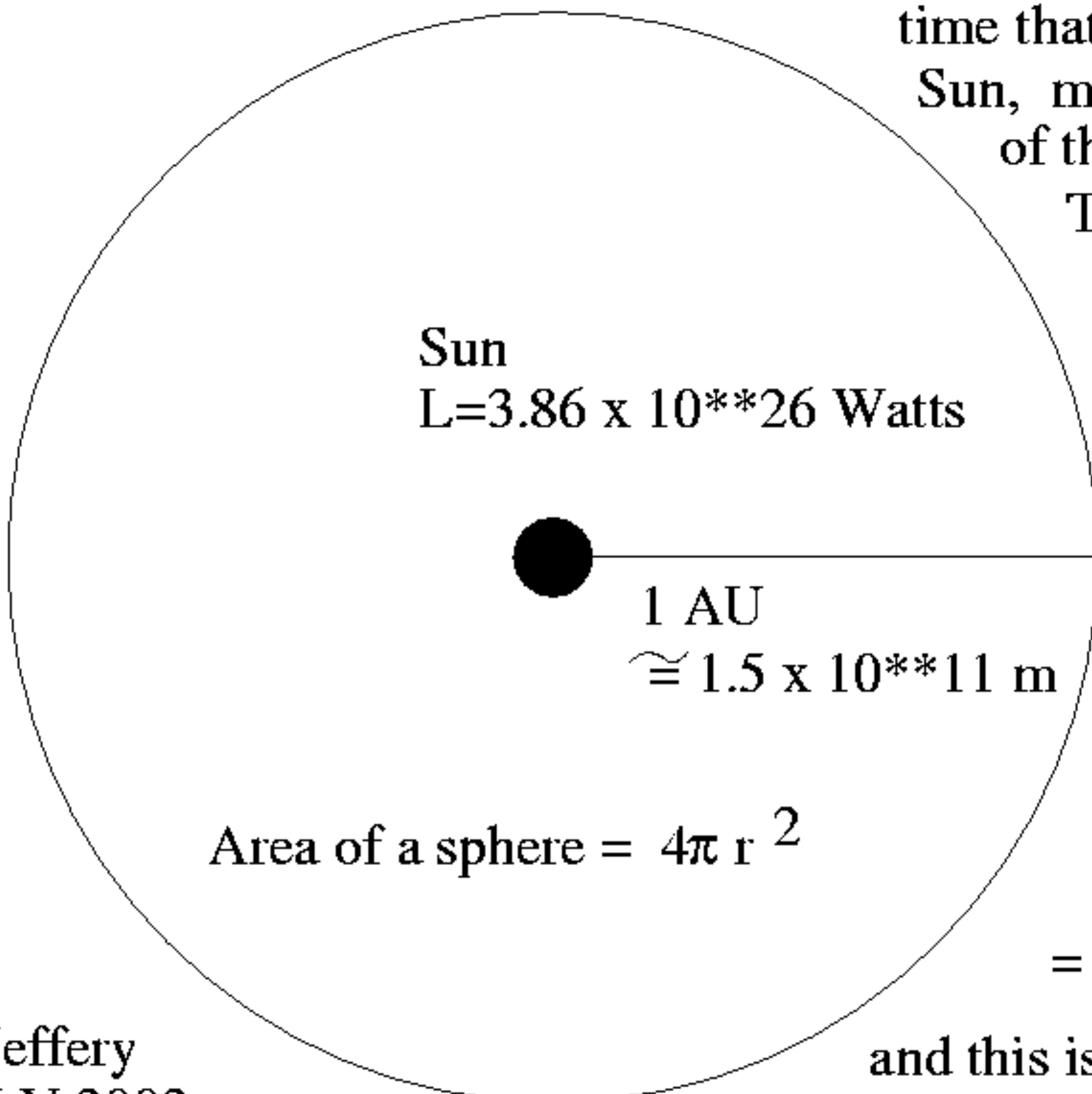
The Slight Elliptical Orbit of the Earth




Ellipticity cannot explain why the Northern &
the Southern hemisphere have opposite seasons

Solar Constant

All the energy per unit time that comes out of the Sun, must also come out of the sphere at 1 AU. This is required by conservation of energy.



The power per unit area at 1 AU is

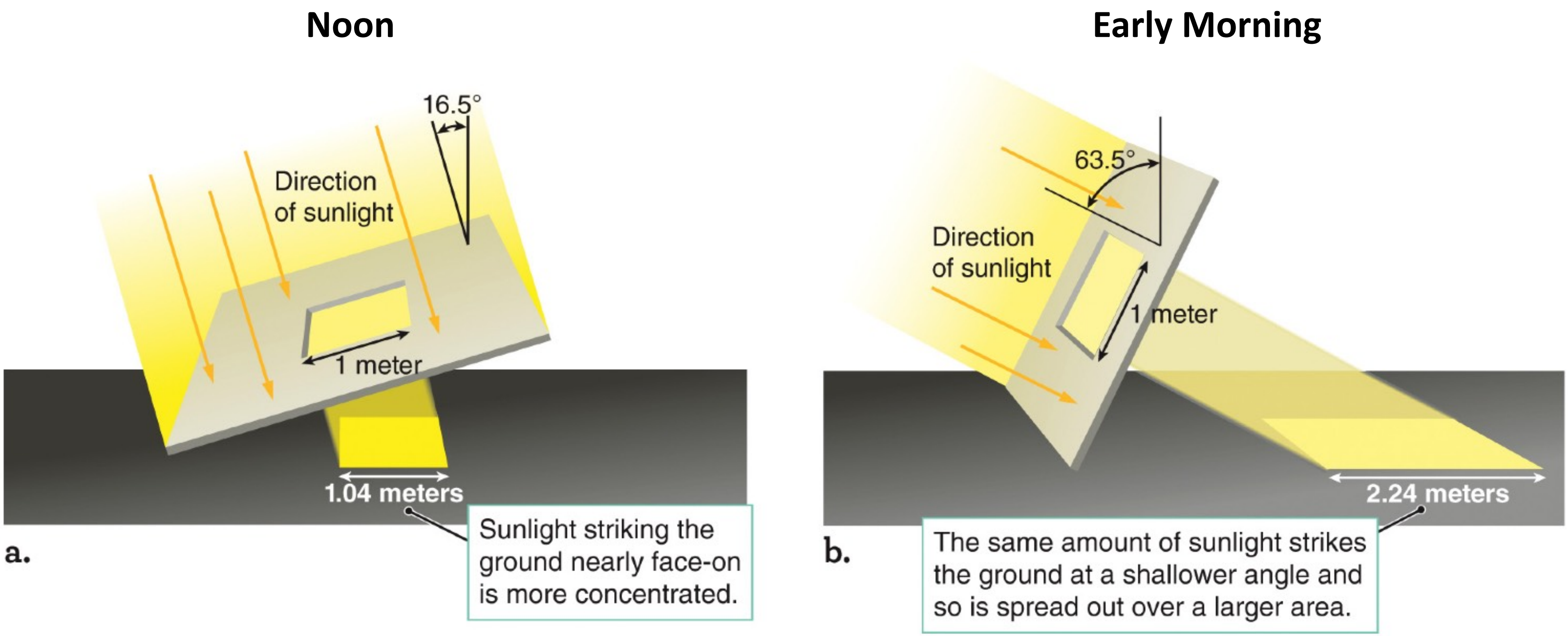
$$\frac{L}{4\pi r^2}$$

= 1366 W/m**2

and this is the Solar Constant.

DJ Jeffery
UNLV 2003

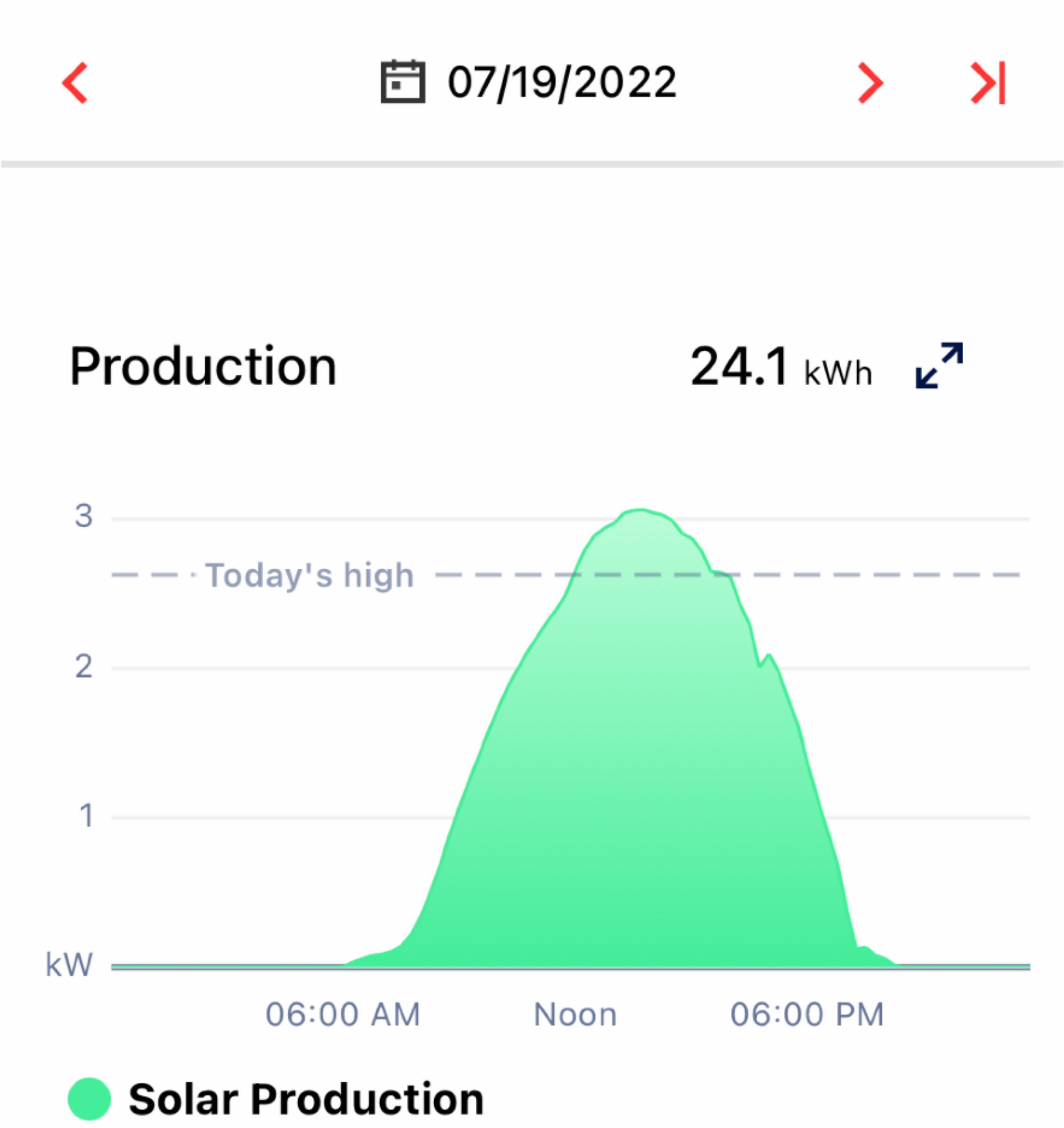
Altitudes of the Sun in the morning vs. noon cause ground temperature to change.



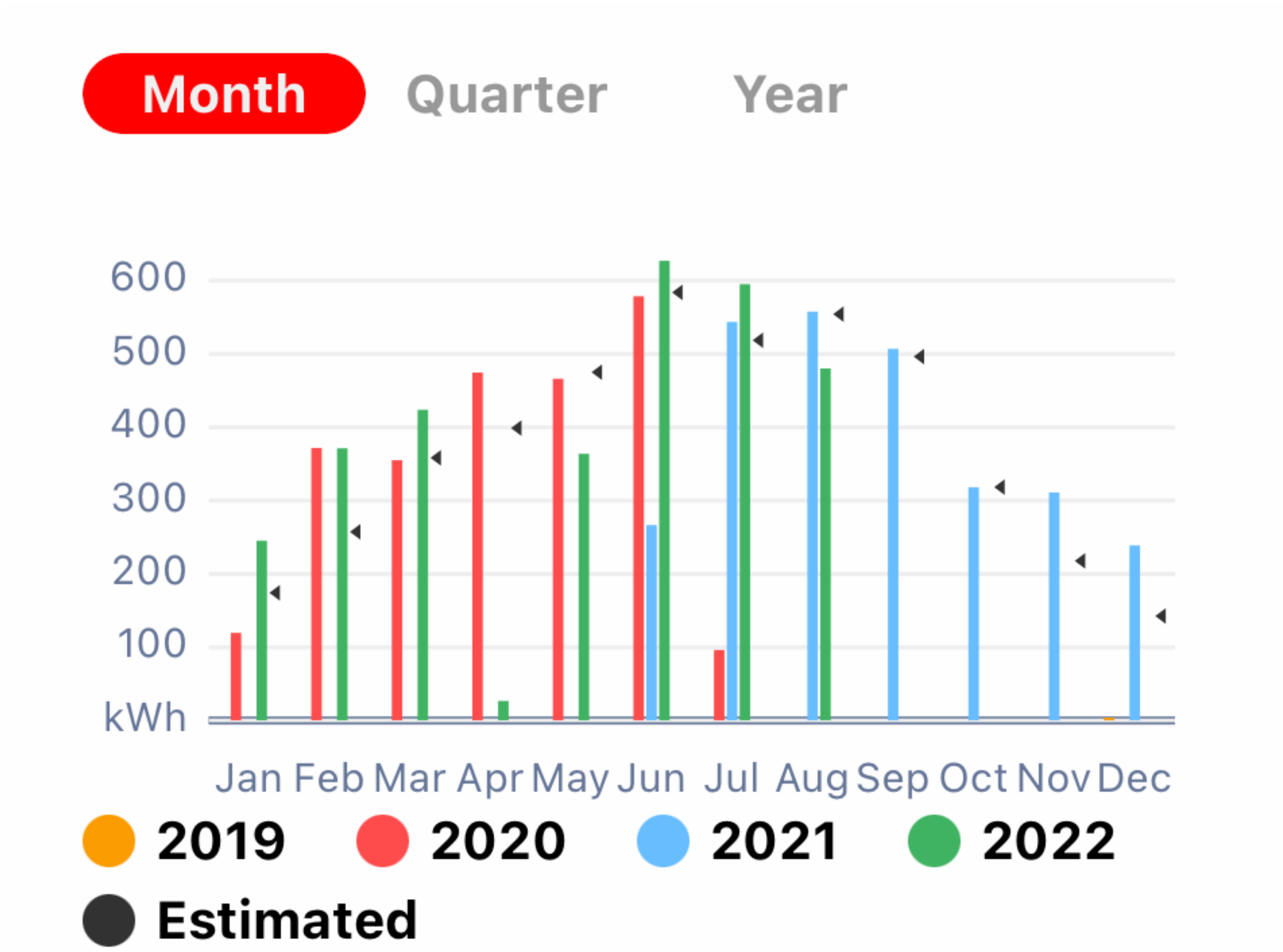
The key is to understand that how energy is distributed on the ground. At lower altitude, the solar energy is more spread out; at higher altitude, it is more concentrated.

Check out solar energy production

Daily Energy Production of My 4 kW Array



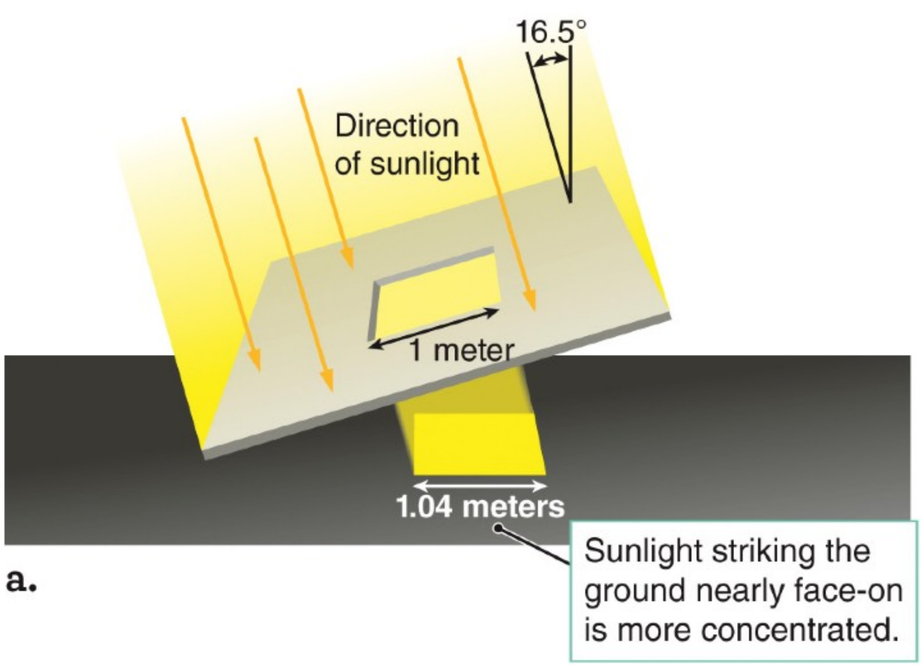
Monthly Production of My Solar Array



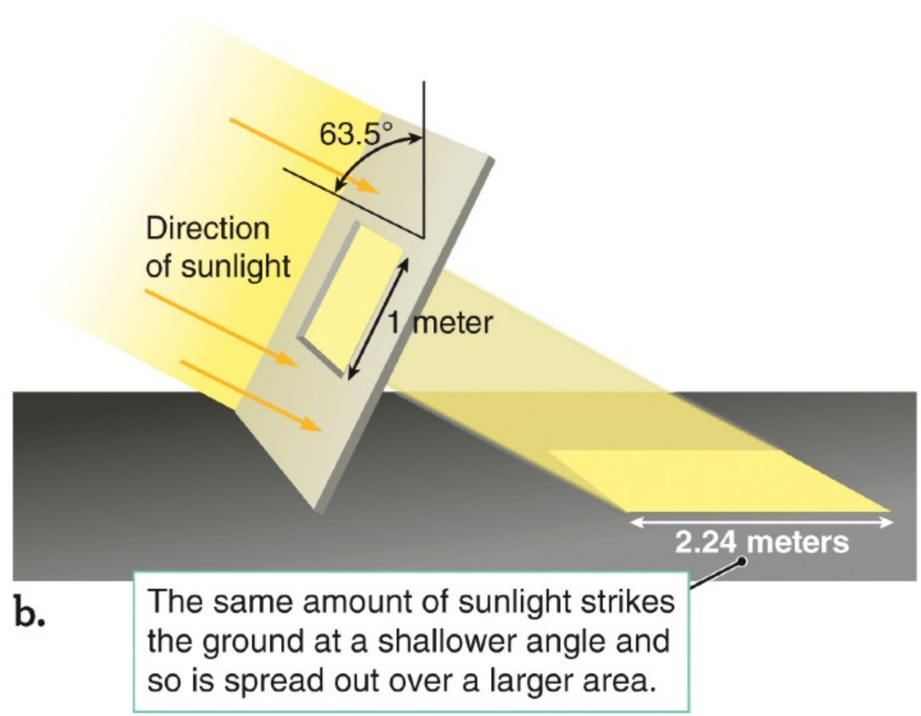
How does the altitude of the Sun affect ground temperature?

The key is to understand that how energy is distributed on the ground. At lower altitude, the solar energy is more spread out; at higher altitude, it is more concentrated.

Noon on Summer Solstice

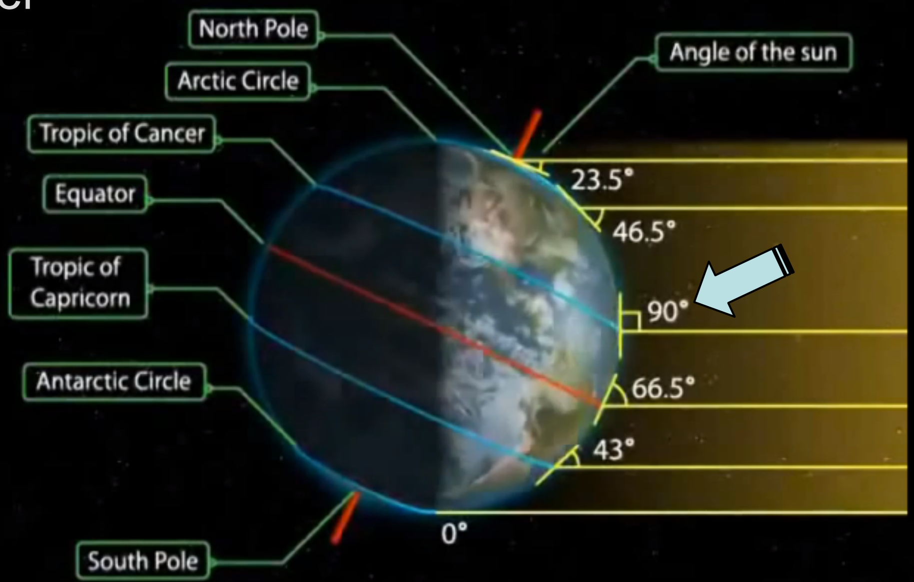


Noon on Winter Solstice

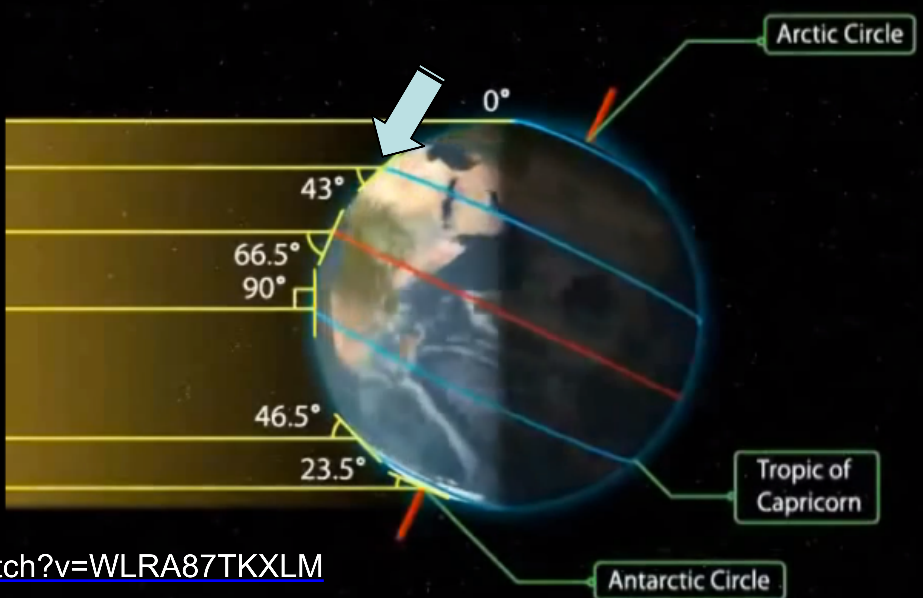


Obliquity & Seasons

Summer

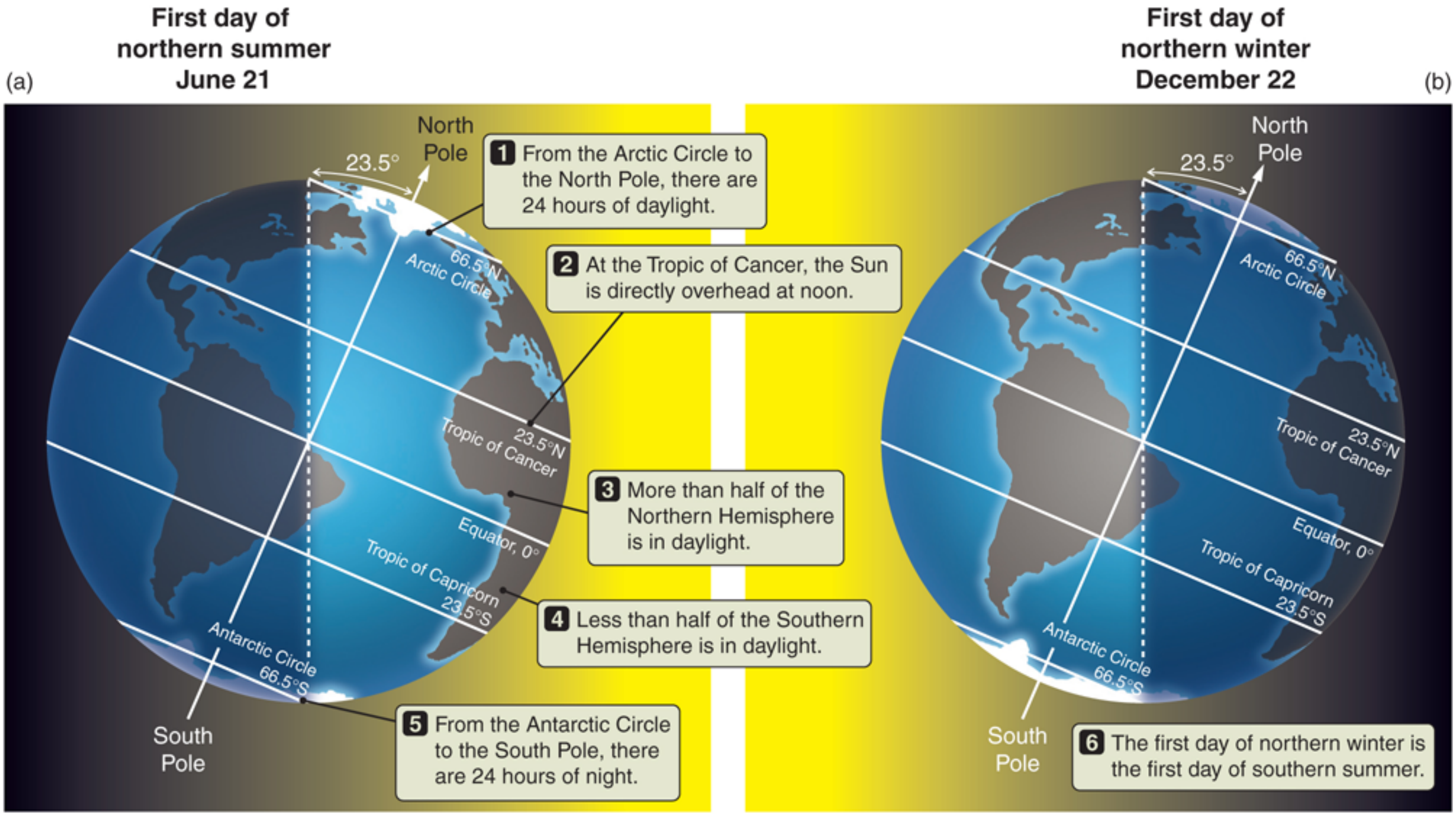


Winter

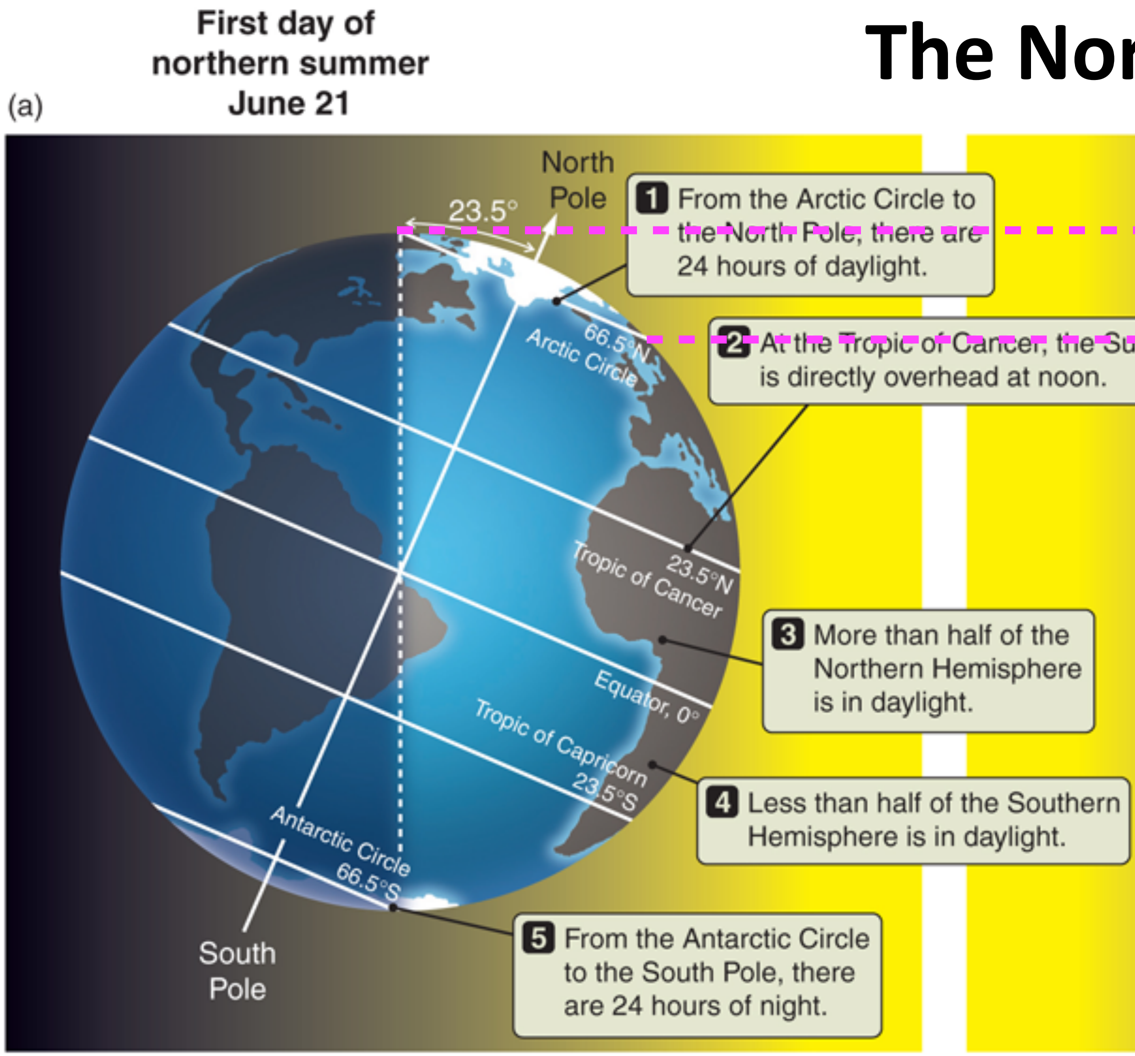


https://www.youtube.com/watch?v=WLRA87TKXLM

Zenith Angle of the Sun in Summer vs. Winter



The Northern Arctic Circle

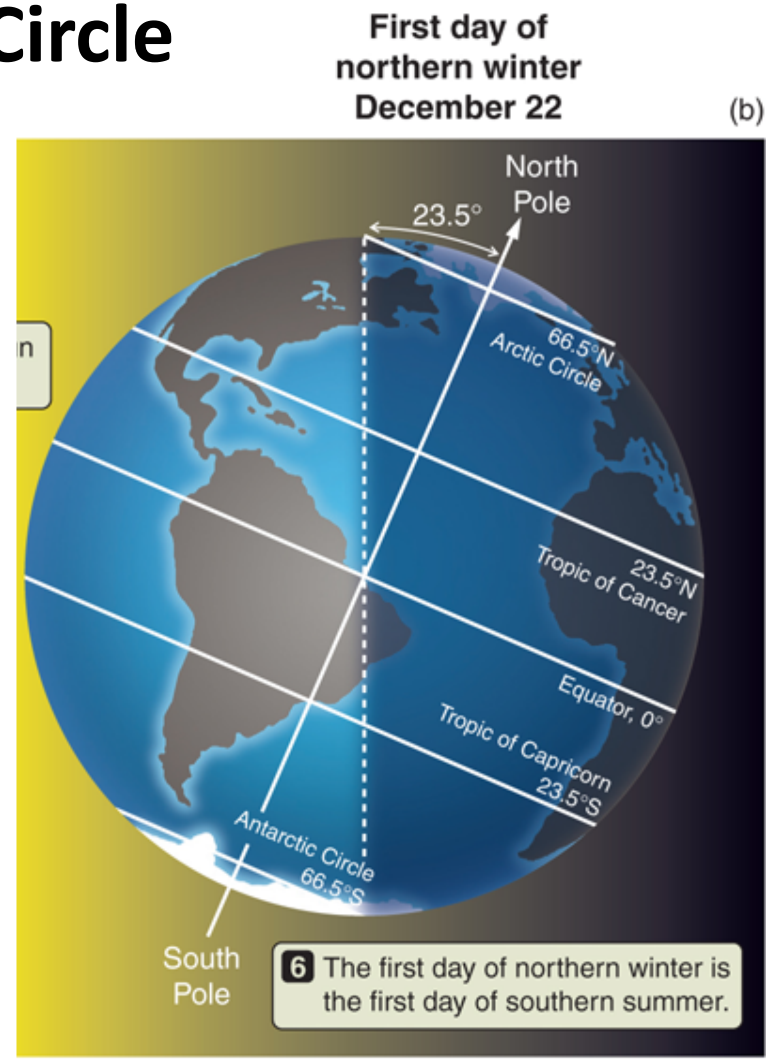


- Seeing the midnight sun in the arctic circle on summer solstice
- Magenta lines: direction towards the Sun at noon and midnight
- arctic circle: latitude > +66.5d

Dr. Juerg Alean/Science Source

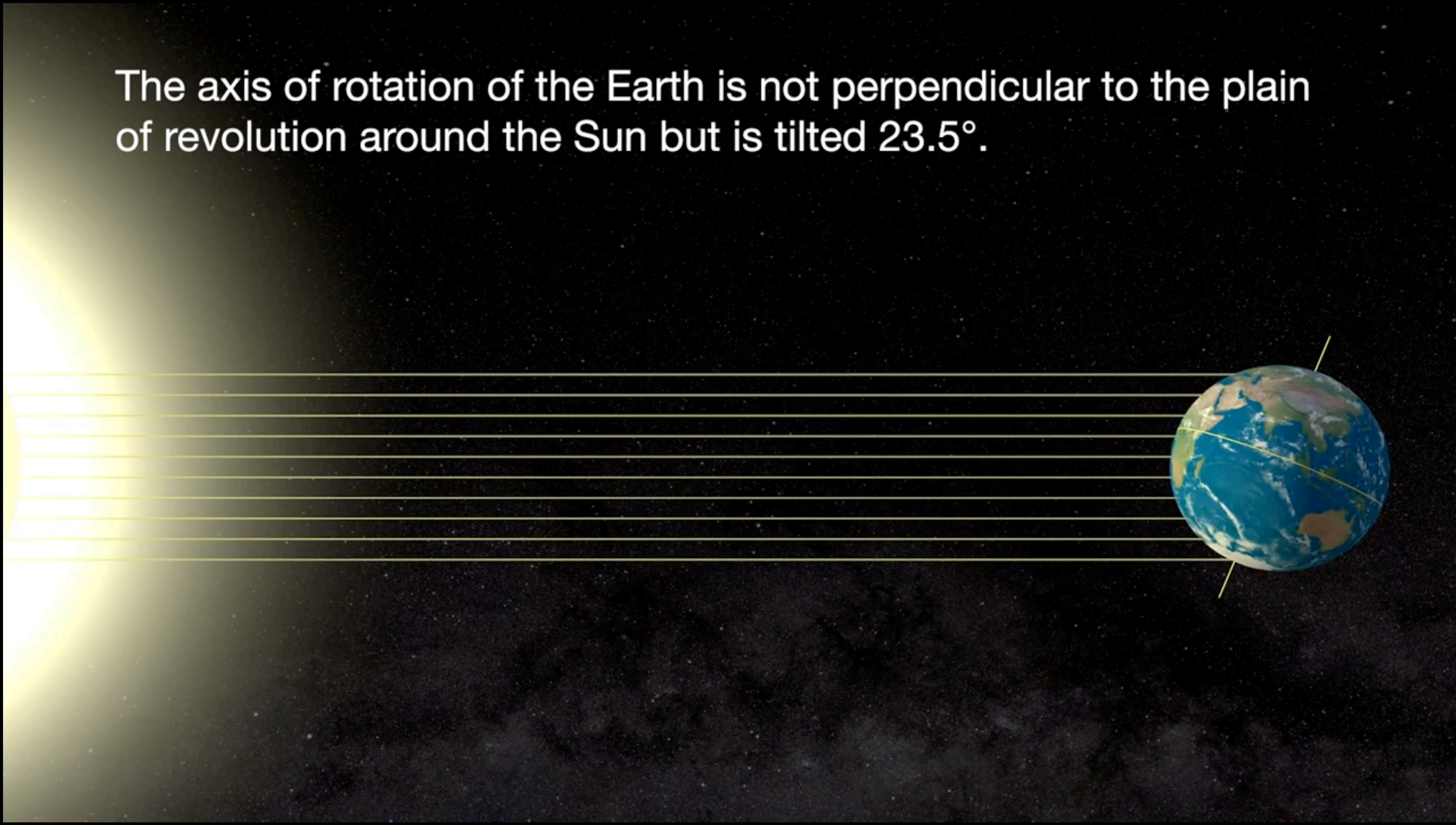
The Southern Arctic Circle

- Seeing the midnight sun in the Antarctic circle on winter solstice
- Antarctic circle: latitude < -66.5d



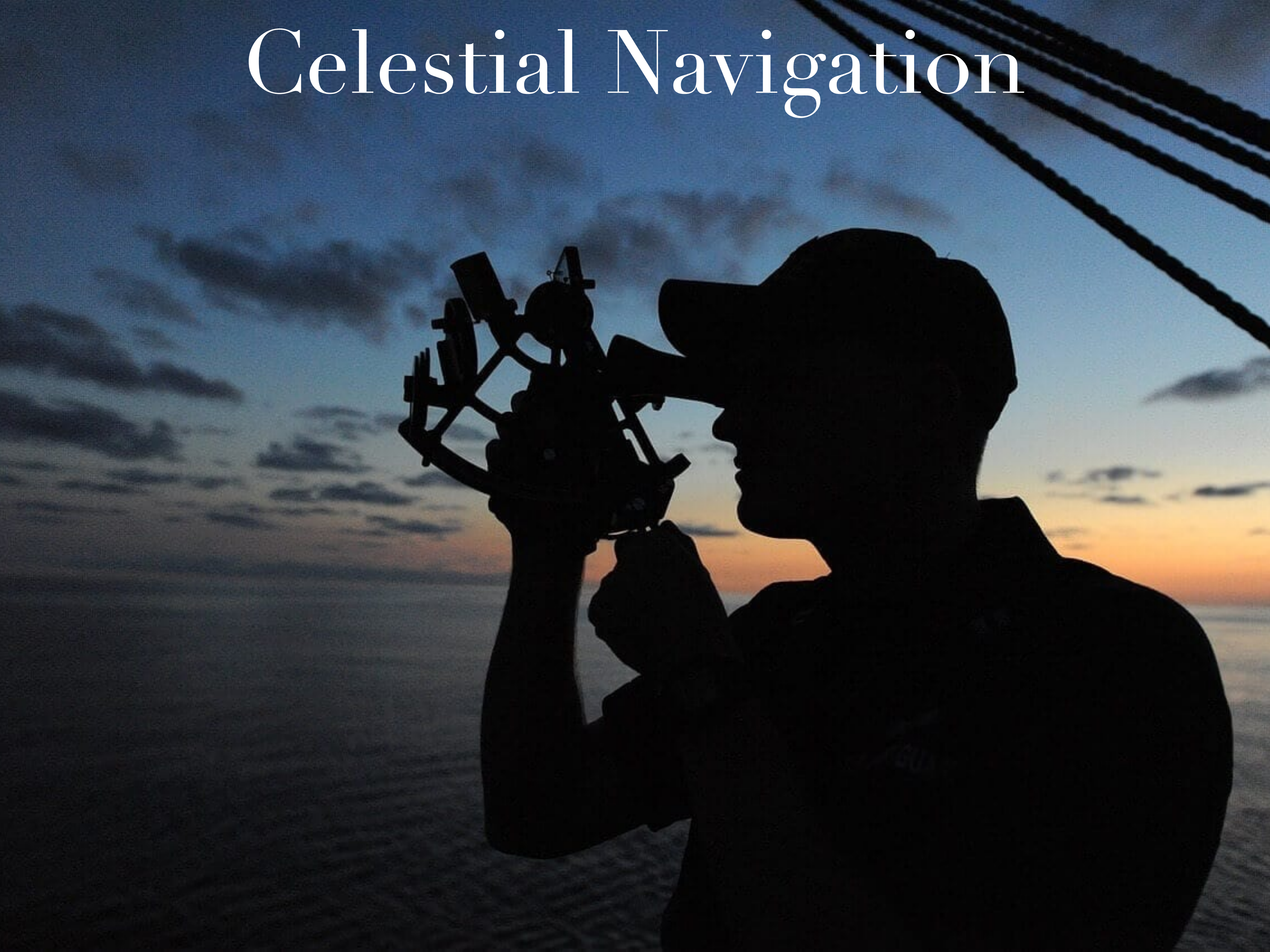
Dr. Juerg Alean/Science Source

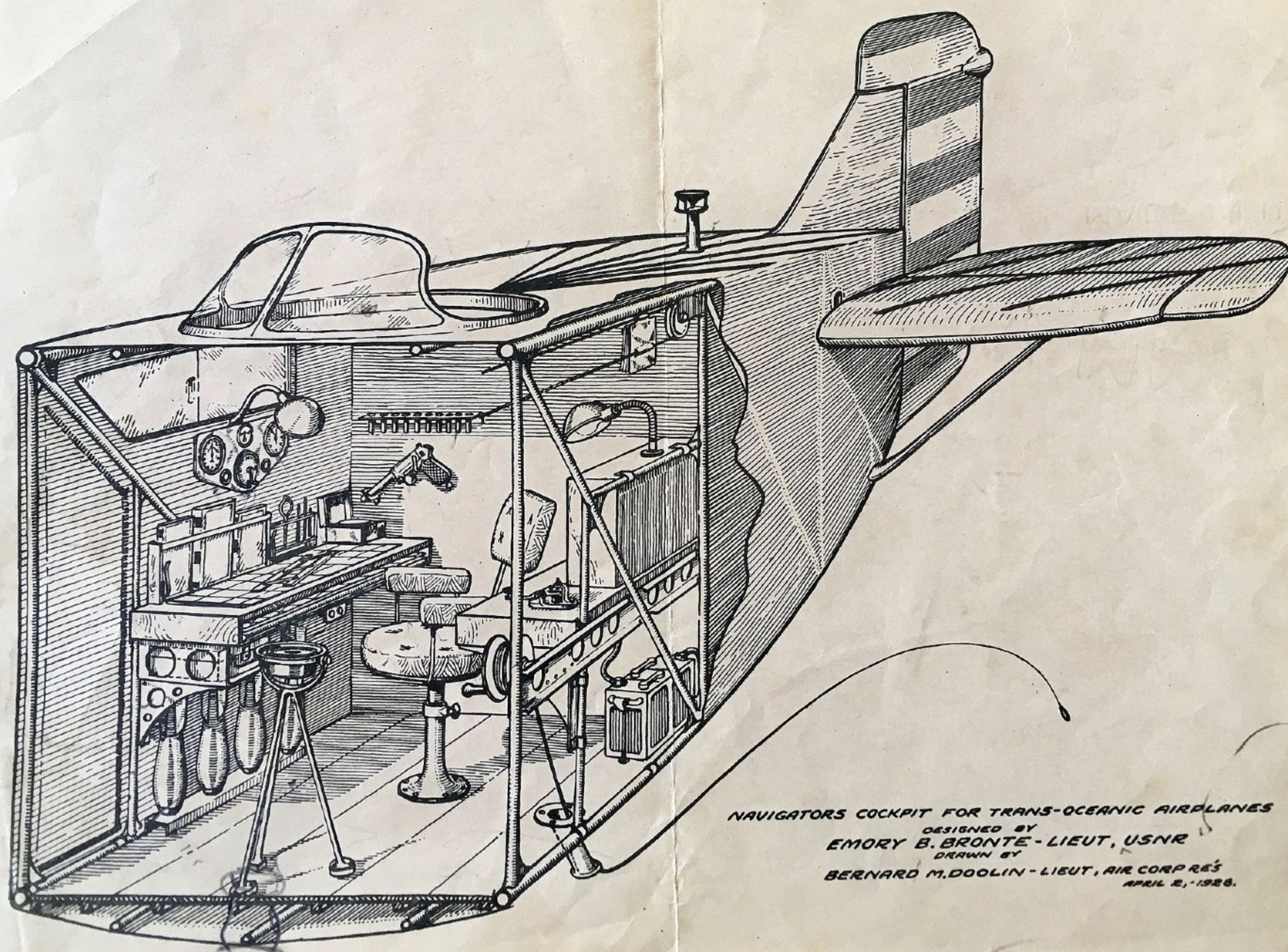
Obliquity & Seasons Animation



Summary: Obliquity & Seasons

- The 23.5-deg obliquity has the following effects on Earth:
  - The angle of sunlight is more direct in summer, thus the received solar energy is higher per unit surface area.
  - The sun stays above the horizon longer in the summer, shorter in the winter, so the ground receives more energy on a summer day
- The ellipticity of the Earth's orbit has negligible effect on the seasons we experience.
- Southern Hemisphere experiences the opposite situation of the Northern Hemisphere.

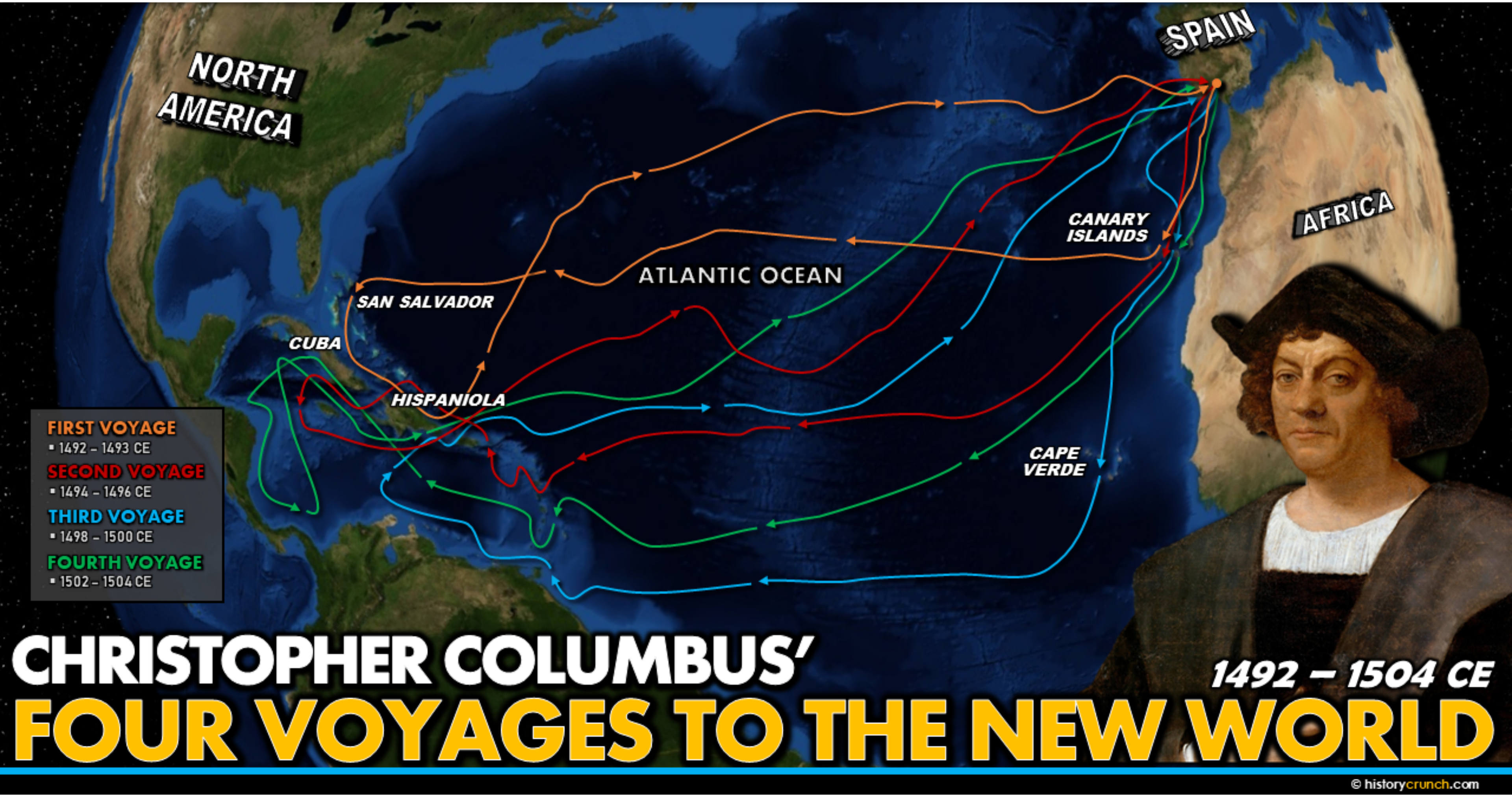

Celestial Navigation



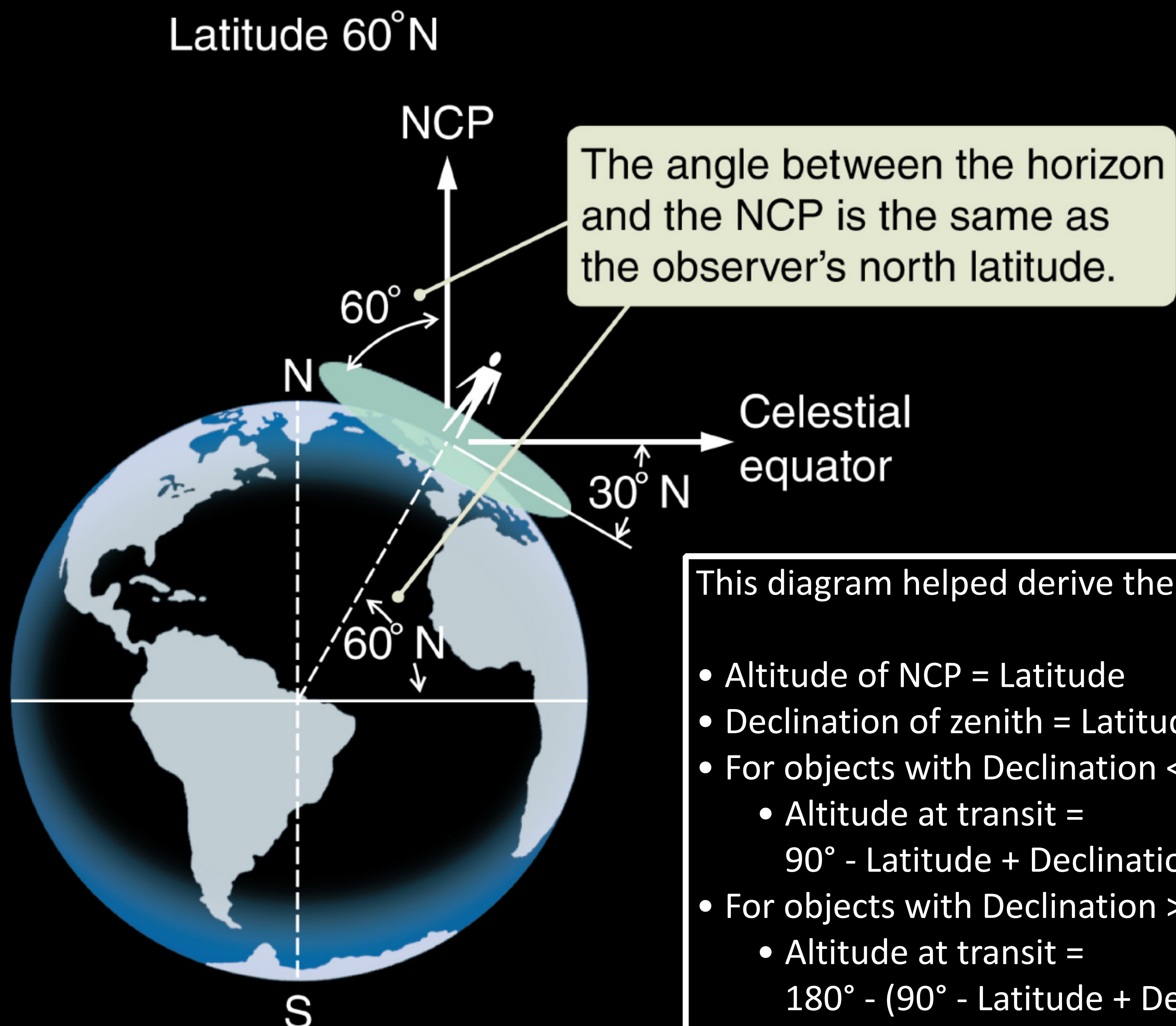
NAVIGATORS COCKPIT FOR TRANS-OCEANIC AIRPLANES
DESIGNED BY
EMORY B. BRONTE - LIEUT, USNR
DRAWN BY
BERNARD M. DOOLIN - LIEUT, AIR CORP RE'S
APRIL 2, - 1928.


C

- To navigate through the sea, we need to know both our **latitude** and our **longitude**.
- To measure **latitude**, we can use the **altitude** of Polaris, the **altitude** of the Sun at noon given the date, or the **declination** of a star near zenith
- To measure **longitude**, we need a clock that measures the precise **local time** at a known geological location (home port). That local time could be either **sidereal time** (for nighttime navigation) or **solar time** (for daytime navigation).



LATITUDE:
ALTITUDE OF NCP
DECLINATION OF ZENITH
ALTITUDE OF SUN



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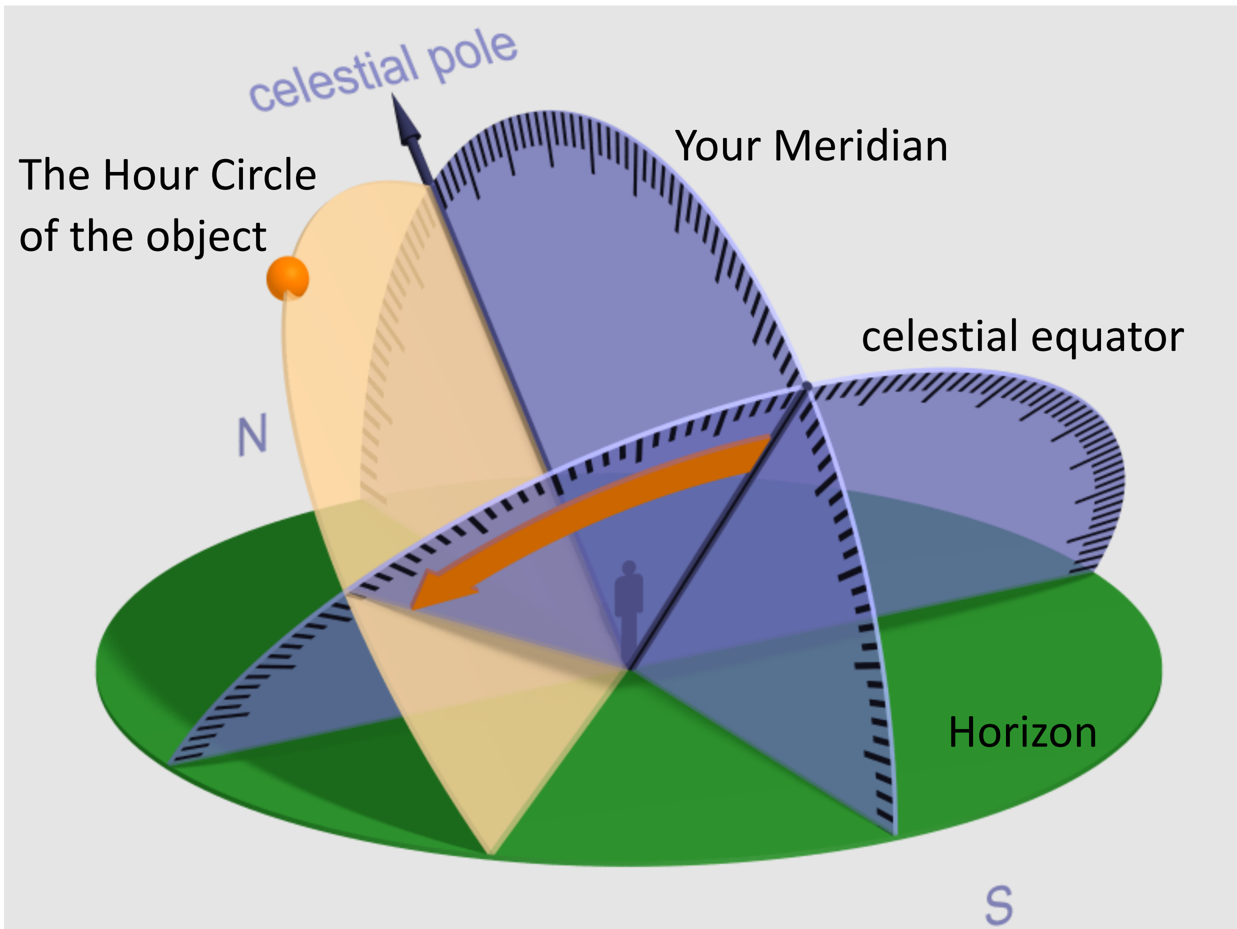
- For objects with Declination < Latitude
  - Altitude at transit = 90° - Latitude + Declination
- For objects with Declination > Latitude
  - Altitude at transit = 180° - (90° - Latitude + Declination)

THE ASTRONOMICAL DEFINITION OF TIME

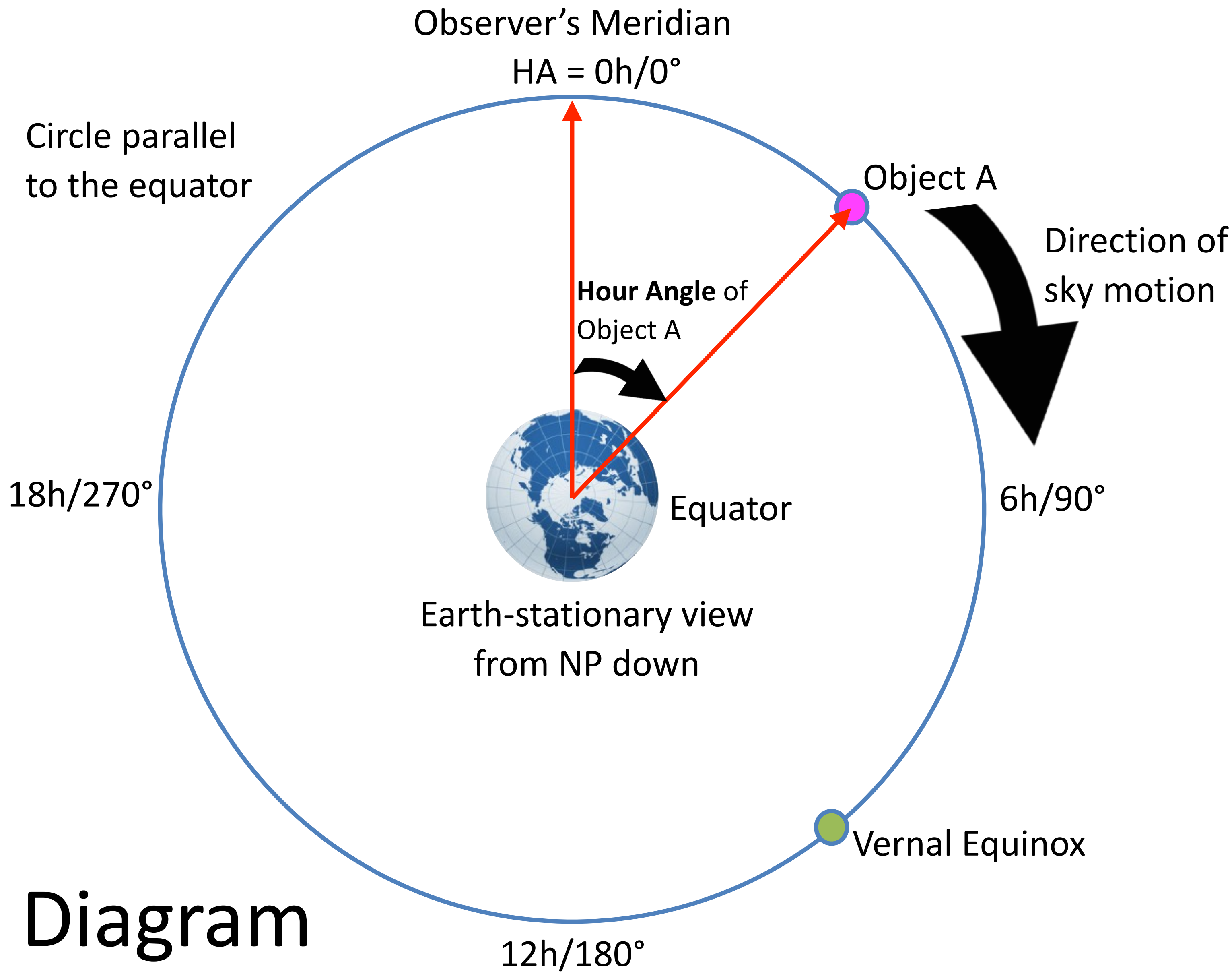
Time is the Hour Angle of Celestial Objects

To keep time, we use **Hour Angle**

- **hour angle (*h*)** is measured **to the west** from the **local meridian** to the **hour circle** passing through the object (Unit: hr or deg)
- **hour circle**: the great circle through a given object and the two celestial poles



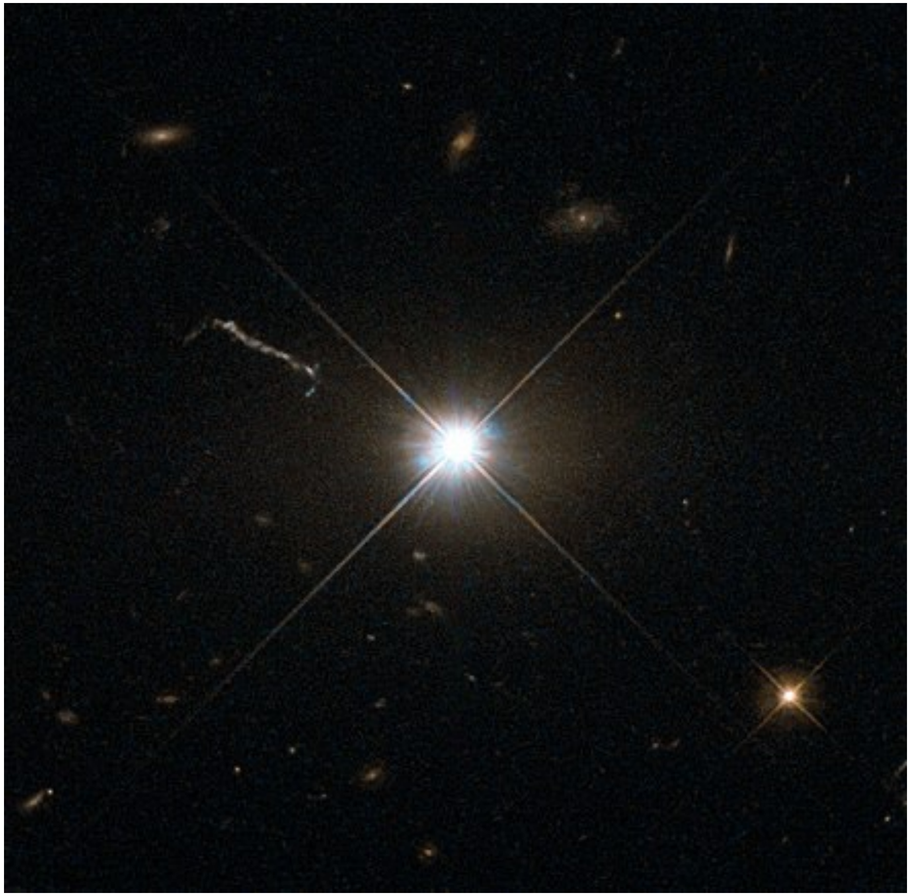
Hour Angle is the angle measured to **clockwise** from the **local meridian** to the **hour circle** passing through the object. The diagram below shows that $HA_{Obj} = RA_{Meridian} - RA_{Obj}$, since both HA and RA are measured along the equator but measured in opposite directions.



Time Diagram

Practice: Hour Angle Calculation

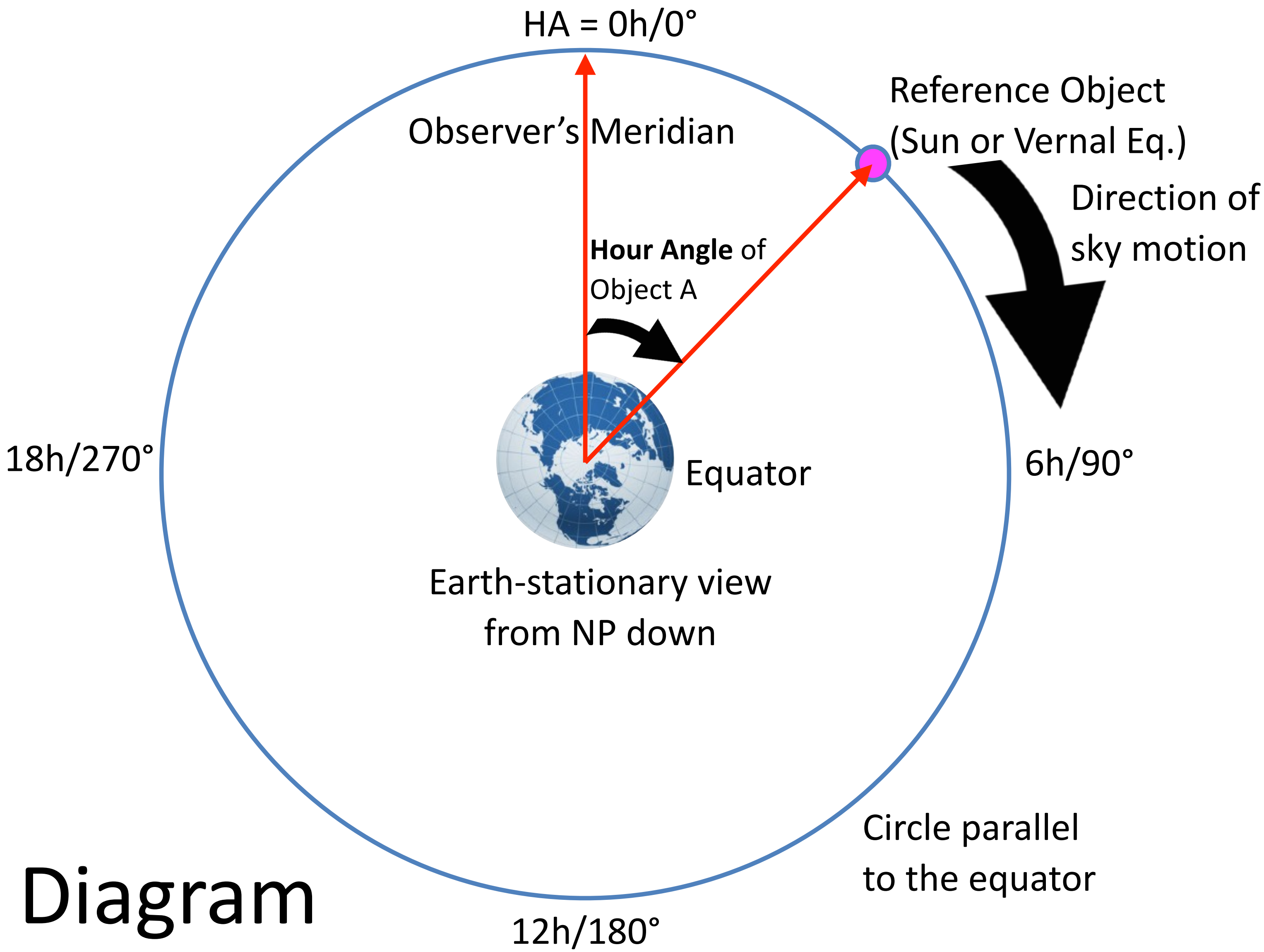
- Quasar 3C 273 is at RA = 12h29m, Dec = +02d
- Your Zenith is at RA = 7h40m Dec = +42d
- What is the hour angle of 3C 273?



- HA(Obj) = RA(Meridian) - RA(Obj)

Time is the **Hour Angle** of a **reference celestial object:**

If the object is the Sun, we have the **Apparent Solar Time**;
If the object is the Vernal Equinox, we have **Local Sidereal Time.**



Time Diagram

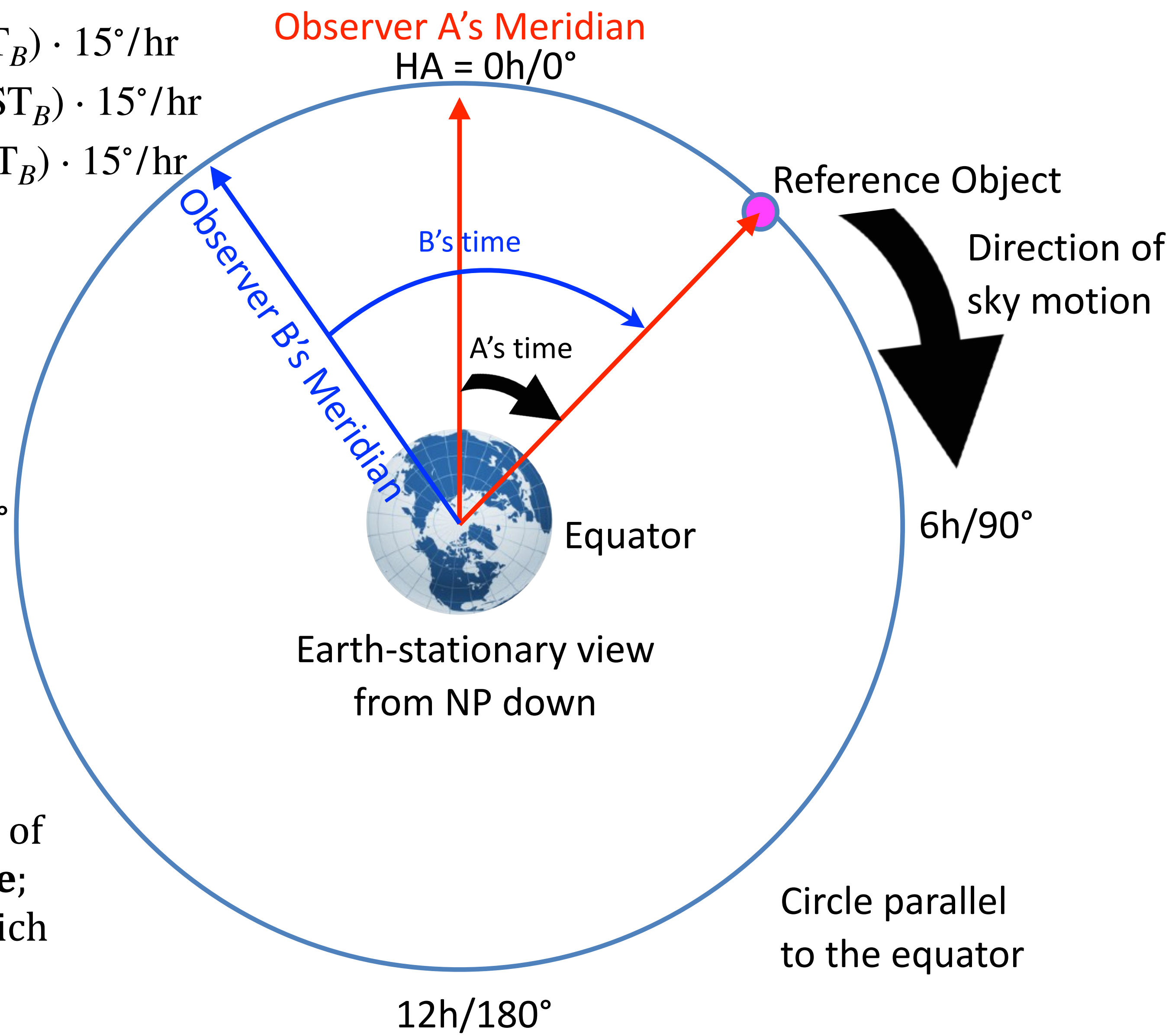
Longitude difference is time difference:

make sure to compare the same kind of time

$$\lambda_A - \lambda_B = (\mathrm{LST}_A - \mathrm{LST}_B) \cdot 15°/\mathrm{hr}$$

$$\lambda_A - \lambda_B = (\mathrm{MST}_A - \mathrm{MST}_B) \cdot 15°/\mathrm{hr}$$

$$\lambda_A - \lambda_B = (\mathrm{AST}_A - \mathrm{AST}_B) \cdot 15°/\mathrm{hr}$$



Longitudes to the **East** of Greenwich are **positive**; to the **West** of Greenwich are **negative.**

ΔLONGITUDE FROM ΔSIDEREAL TIME

Local Sidereal Time (LST)

- Definition:

  $LST :=$ Hour Angle of the Vernal Equinox

  $= RA_{Meridian} - RA_{Ver.\ Eq.}$

  $\Rightarrow$

  $LST = RA_{Meridian}$

- As shown on the Time Diagram, we can calculate the HA of any object using a local sidereal clock:

  $HA_{Obj} = RA_{Meridian} - RA_{Obj} = LST - RA_{Obj}$

- Rearranging the above relation, we realize that we can also measure the LST using any objects, not necessarily on the meridian:

  $LST = RA_{Obj} + HA_{Obj}$

Celestial Coordinates of the Local Zenith

Local Sidereal Time
7:17:09

UTC
14:16:43

Longitude: -91.5323

What is Sidereal Time?

localsiderealtime.com

RA_{Zenith} = LST

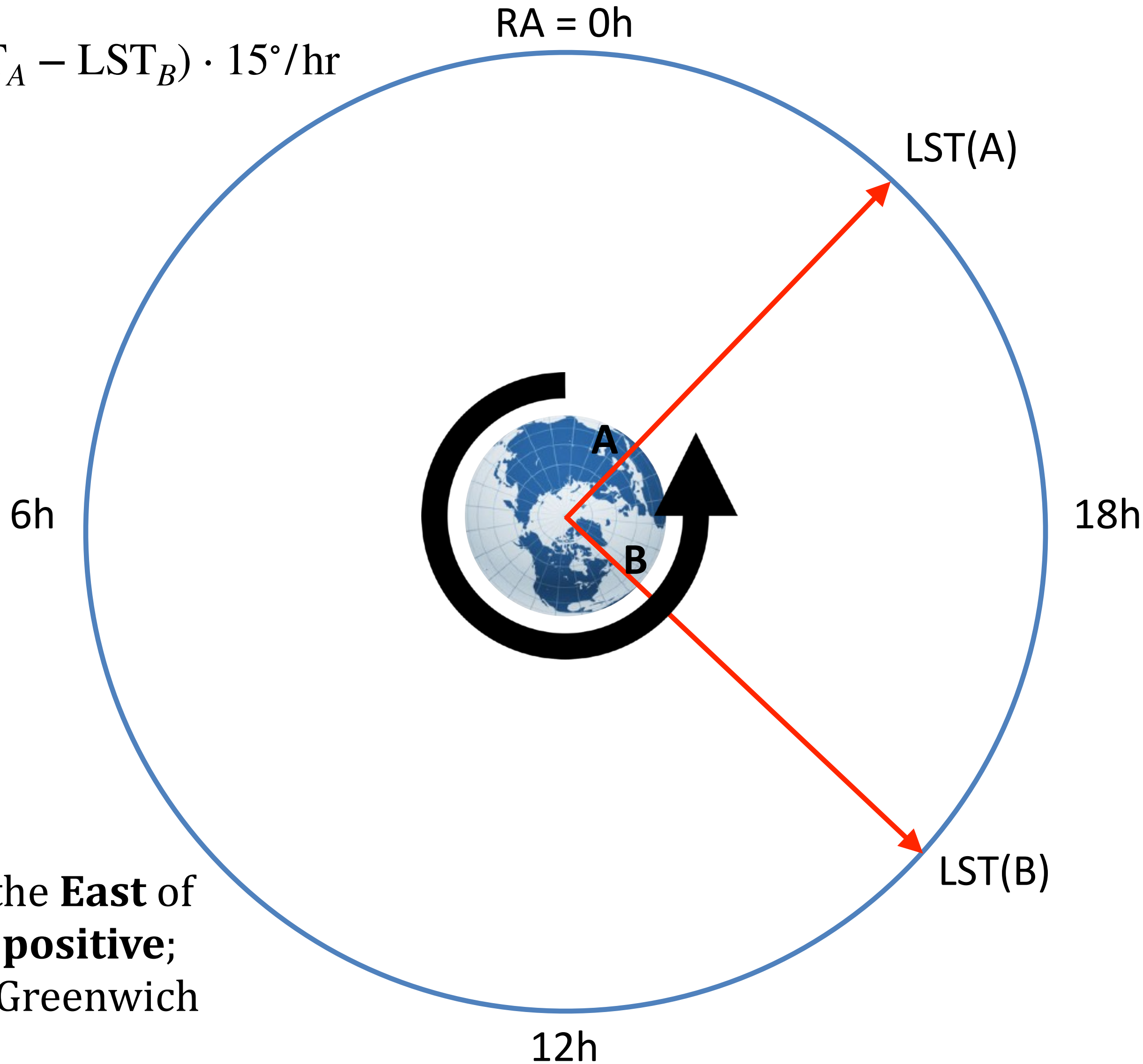
The LST tells us the RA of the Zenith because the Zenith is on the Meridian

Dec_{Zenith} = Latitude

The Latitude tells us the Declination of the Zenith

Difference in Longitude = Difference in Sidereal Time x 15°/hr

$$\lambda_A - \lambda_B = (\mathrm{LST}_A - \mathrm{LST}_B) \cdot 15°/\mathrm{hr}$$



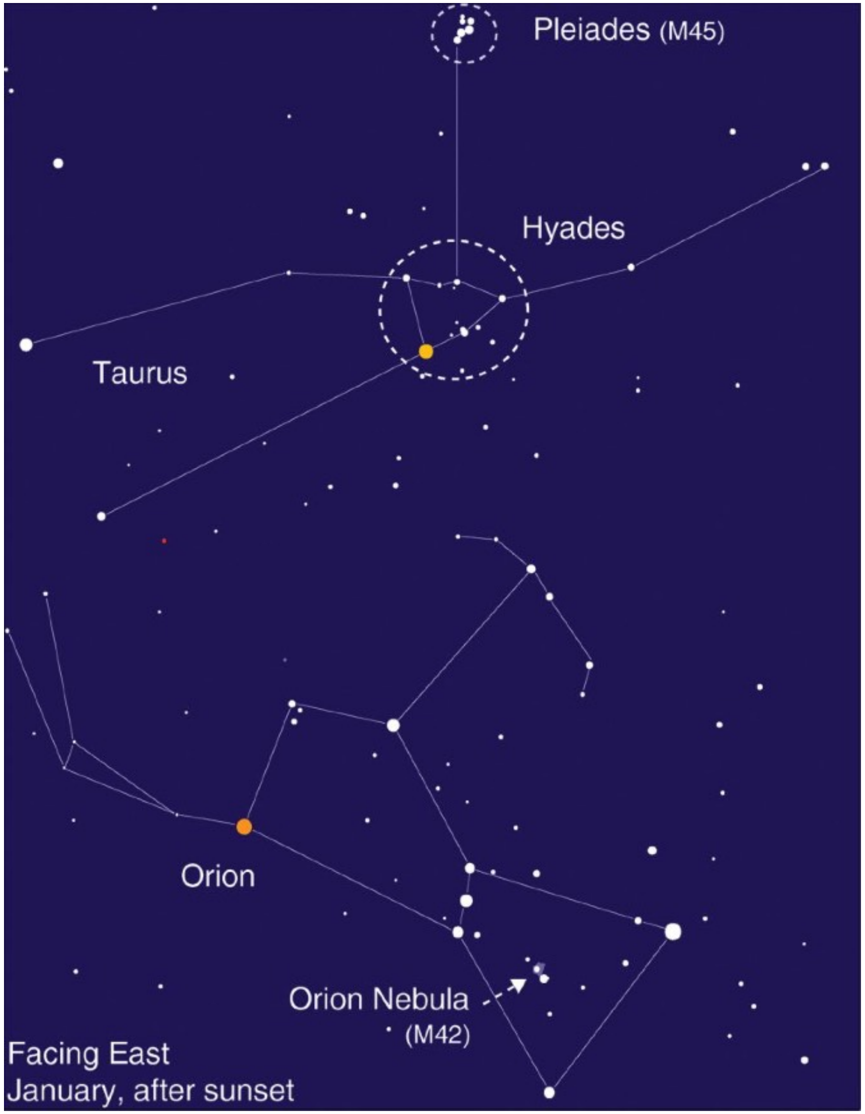
Longitudes to the **East** of Greenwich are **positive**; to the **West** of Greenwich are **negative.**

Celestial Navigation with Star at Zenith

- The simplest way is to find the **(RA, Dec) of a star closest to the Zenith** using a star chart
- You also need a **sidereal clock** that keeps the LST of a place A at a known longitude, often the **GMST (Greenwich Mean Sidereal Time; $\lambda_A = 0°$).**
- Your current location B's longitude (λ) and latitude (φ) can then be calculated as:
  - λ(B)-λ(A) = [LST(B) - LST(A)] x 15°/hr
    = [RA(Zenith) - LST(A)] x 15°/hr
  - φ(B) = Dec(Zenith) = Alt(NCP)
- Positive $\Delta\lambda$ means B is to the East of A.

Practice: Celestial Navigation with Objects near Zenith

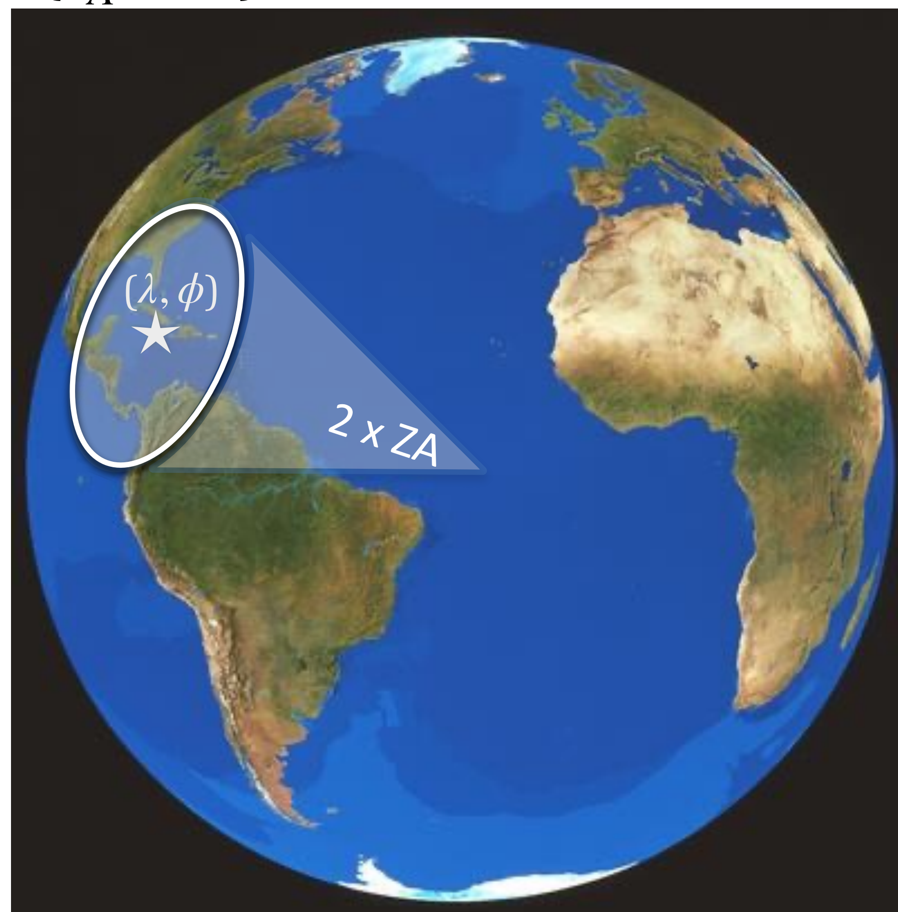
- At an unknown location, you saw Pleiades directly overhead. You then looked up its coordinates with a star chart you carried:
  - Pleiades cluster (M45)
    RA 3h47m, Dec +24.1°
- You also carried a sidereal clock calibrated to the LST of Iowa City at Longitude = 91.5° W and Latitude = 41.6° N. The sidereal clock reads
  - LST of Iowa City = 23:17
- What are your geological coordinates?
  - Latitude = ?
  - Longitude = ?
- Equation:
  - $\lambda(B)-\lambda(A) = [LST(B) - LST(A)] \times 15deg/hr$, where Positive $\Delta\lambda$ means B is to the East of A.

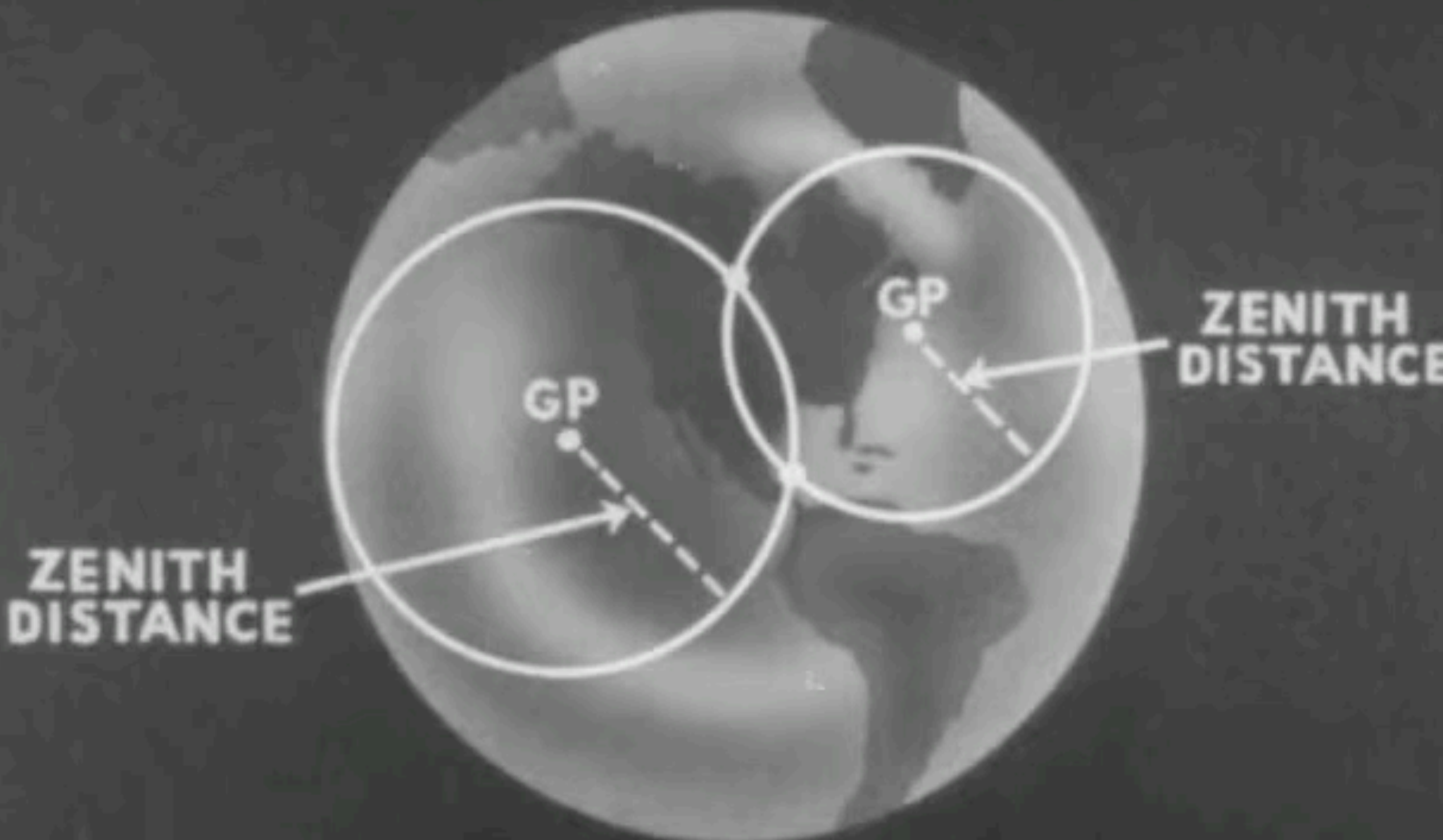


Celestial Navigation with Stars not on Zenith

- The more practical way is to measure the **zenith angle of a bright star (ZA = 90°-Alt)**, for which you know its **(RA, Dec)** from a chart
- You also need a **sidereal clock** that keeps the **LST** of a place A with a known longitude, often the **GMST ($\lambda_A = 0°$).**

- The (RA, Dec) of the star and GMST tell us the geological location of the place on Earth where the star is at its zenith:
  - $\lambda = (\mathrm{RA} - \mathrm{GMST}) \cdot 15°/\mathrm{hr}$
  - $\phi = \mathrm{Dec}$
- **Your location must be along the circle centered on (λ, ϕ) with a radius of the Zenith Angle you measured.**





WWII U.S. ARMY AIR FORCE TRAINING

Celestial Navigation with Two Stars

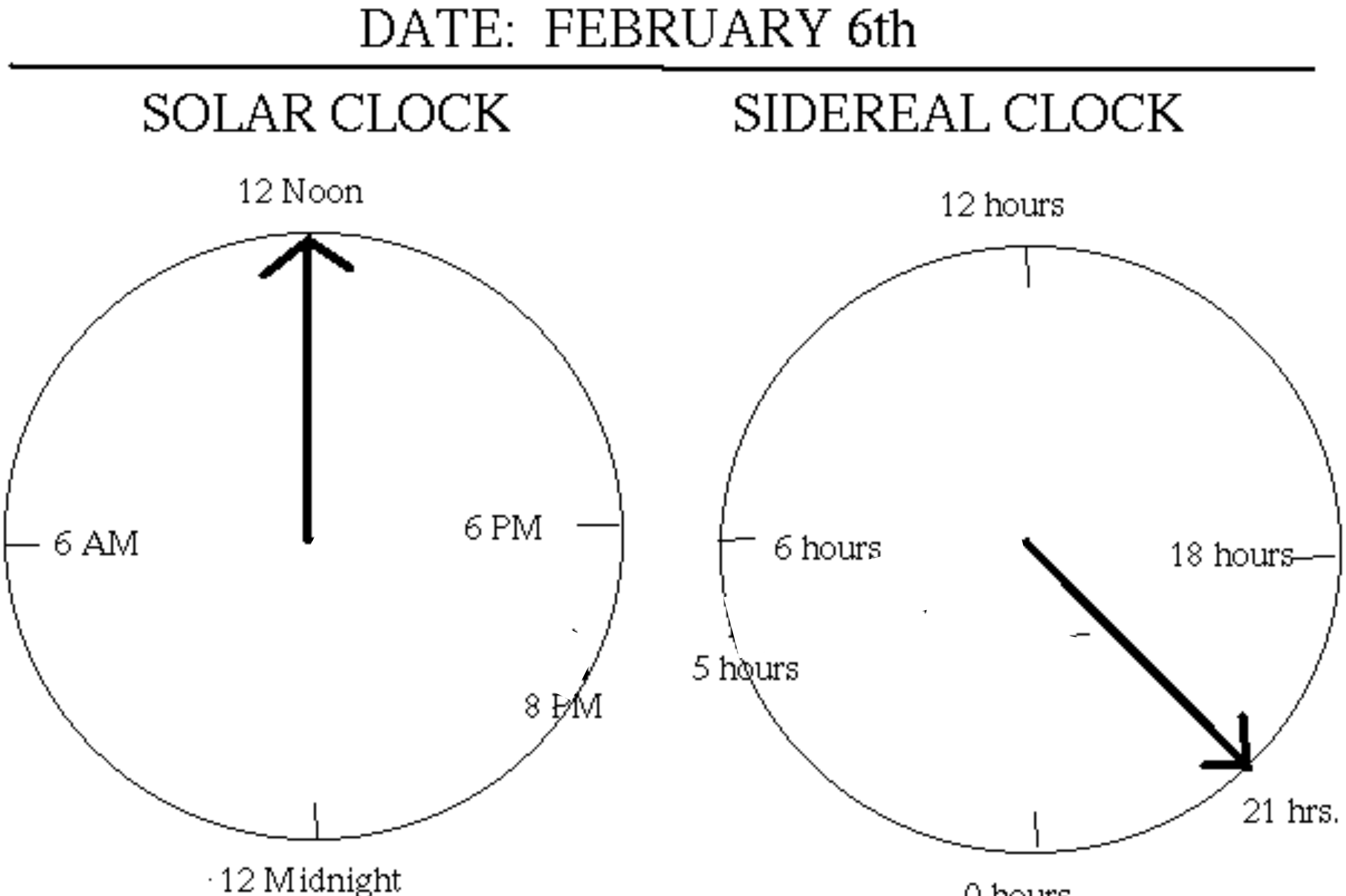
- The more practical way is to measure the **zenith angles of two bright stars (ZA = 90°-Alt)**, for which you know their **(RA, Dec)** from a star chart
- You also need a **sidereal clock** that keeps the LST of a place A with a known longitude, often the **GMST ($\lambda_A = 0°$).**
- The (RA, Dec) of the stars and GMST tell us the geological locations of the two places on Earth where the two stars are at their zenith:
  - $\lambda_A = (\mathrm{RA}_A - \mathrm{GMST}) \cdot 15°/\mathrm{hr},$
    $\lambda_B = (\mathrm{RA}_B - \mathrm{GMST}) \cdot 15°/\mathrm{hr}$
  - $\phi_A = \mathrm{Dec}_A, \phi_B = \mathrm{Dec}_B$
- You then draw two circles on the globe, each with a radius equal to the zenith angle you measured. The two circles intersect at two points, and you must be at one of the two positions.
- To break the ambiguity, you can observe the zenith angle of the third star, and draw the third circle.

ΔLONGITUDE FROM ΔSOLAR TIME

Apparent Solar Time vs. Local Sidereal Time

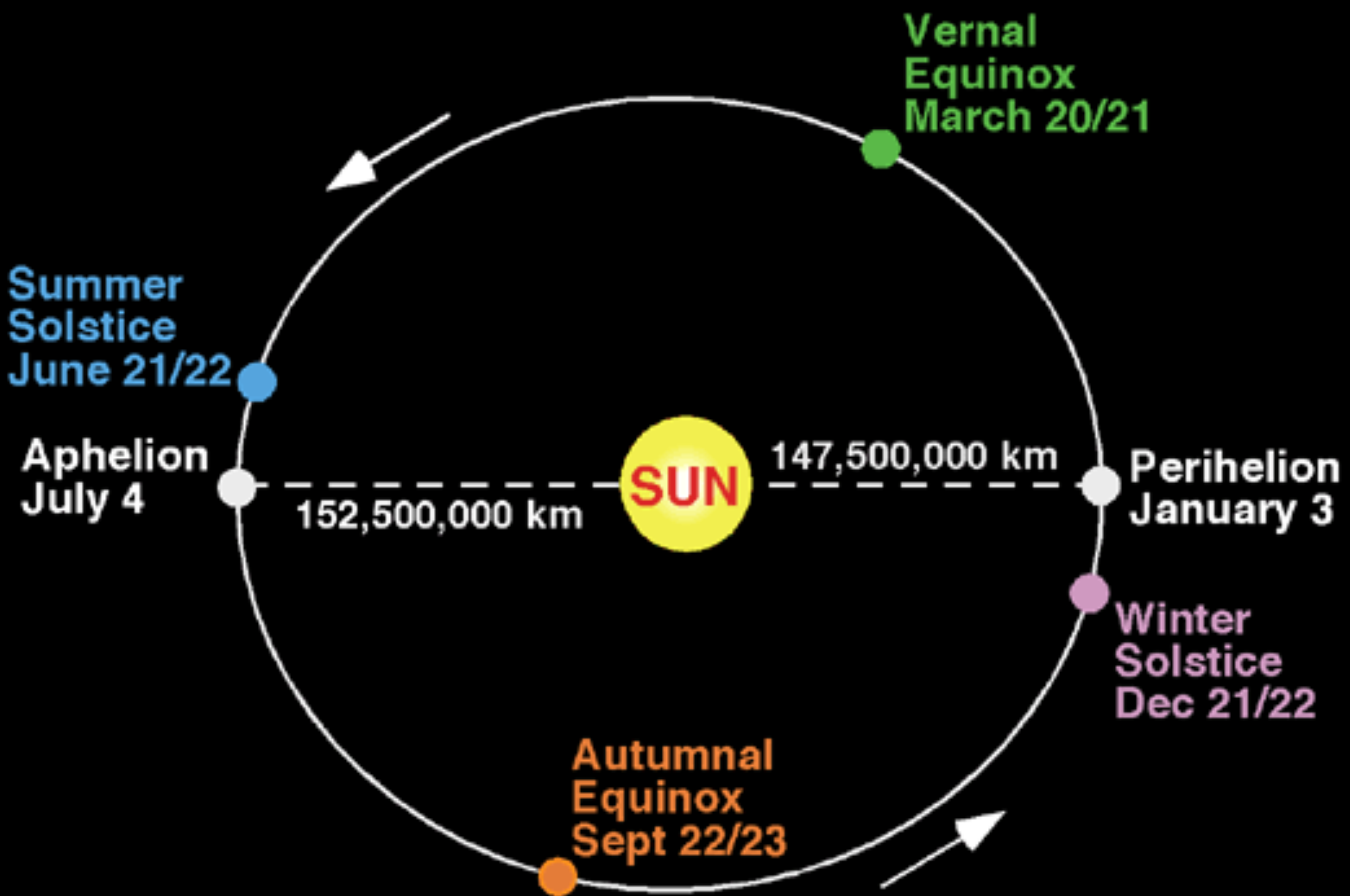
- Apparent Solar Time (AST):
  - AST := 12h + Hour Angle of the Sun
    $= 12h + (RA_{Meridian} - RA_{Sun})$
- Local Sidereal Time (LST):
  - $LST := HA_{Ver.Eq.} = RA_{Meridian}$
- Given the above two equations, we obtain:
  - $\mathbf{AST = LST - RA_{Sun} + 12h}$
  - *Homework Question:*
    on which day, AST equals LST?

Apparent Solar Time vs. Local Sidereal Time



Use the relation, AST = LST - RA_{Sun} + 12h, to check if the illustration is correct.
Or given the illustration, estimate the date.

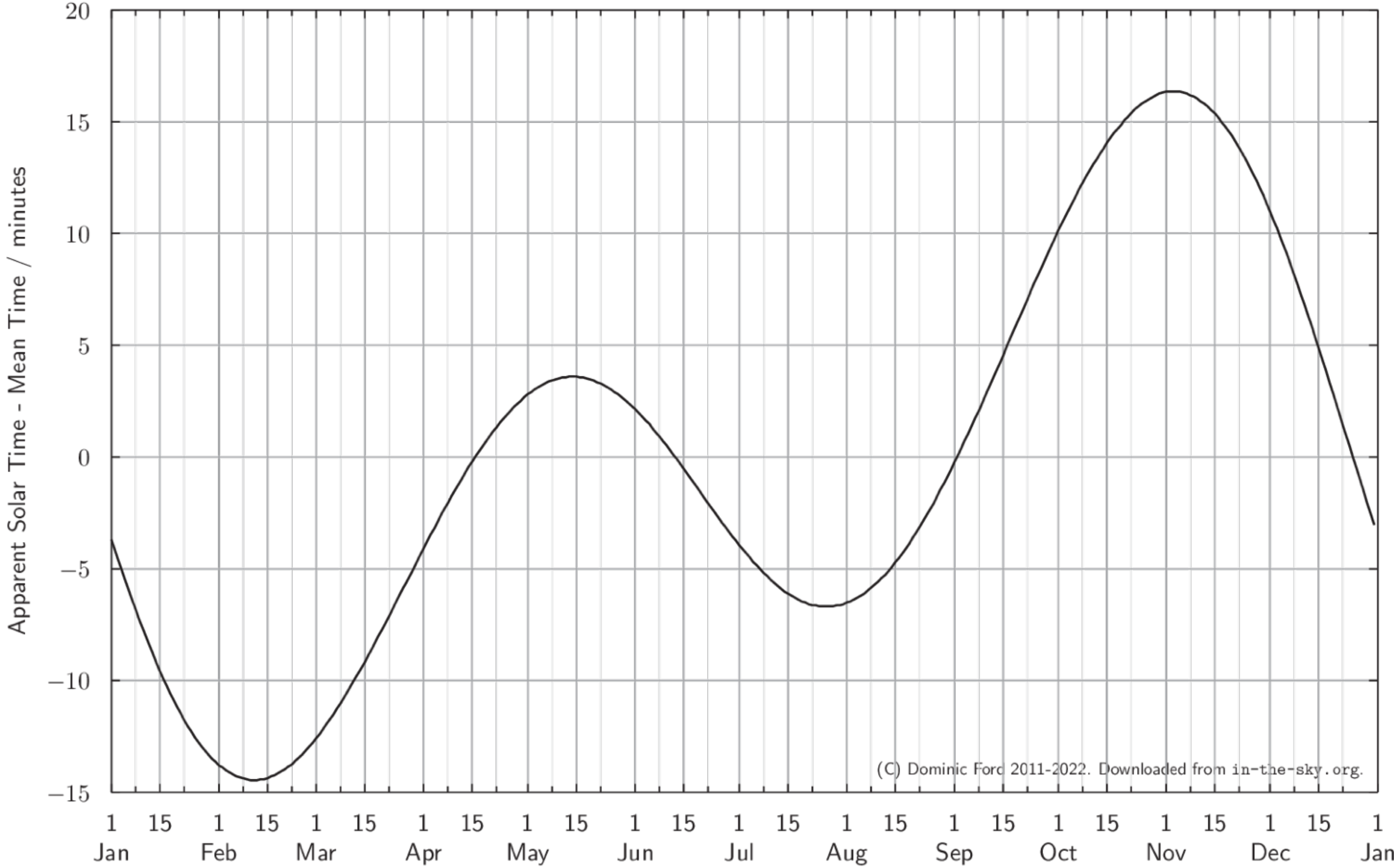
The Length of a Solar Day varies because of the elliptical orbit of the Earth



The Two Types of Local Solar Time

- **Apparent Solar Time (AST)**
  - AST = 12 hrs + (HA of the Sun / 15 deg/hr)
  - Length varies because of the elliptical orbit
- **Mean Solar Time (MST)**
  - Duration defined as the average length of a solar day (*this is the 24 hours we use daily*)
  - Tracks a theoretical **mean Sun** with a uniform motion along the **celestial equator**

Equation of Time: a diagram giving the difference between AST and MST as a function of date in a year

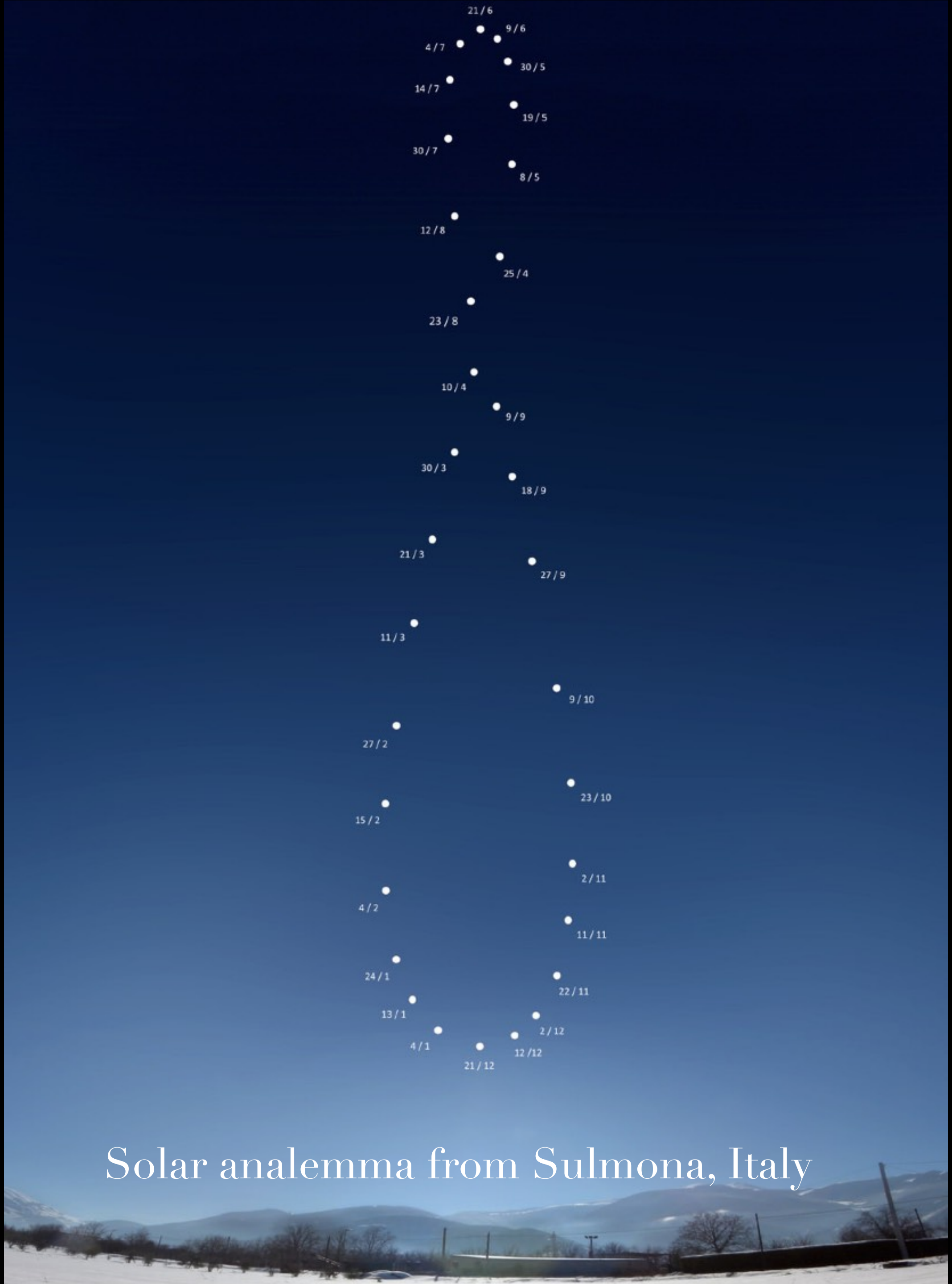


Solar analemma:

A compilation of pictures of the Sun taken at 12PM every ~10 days at the same location on Earth

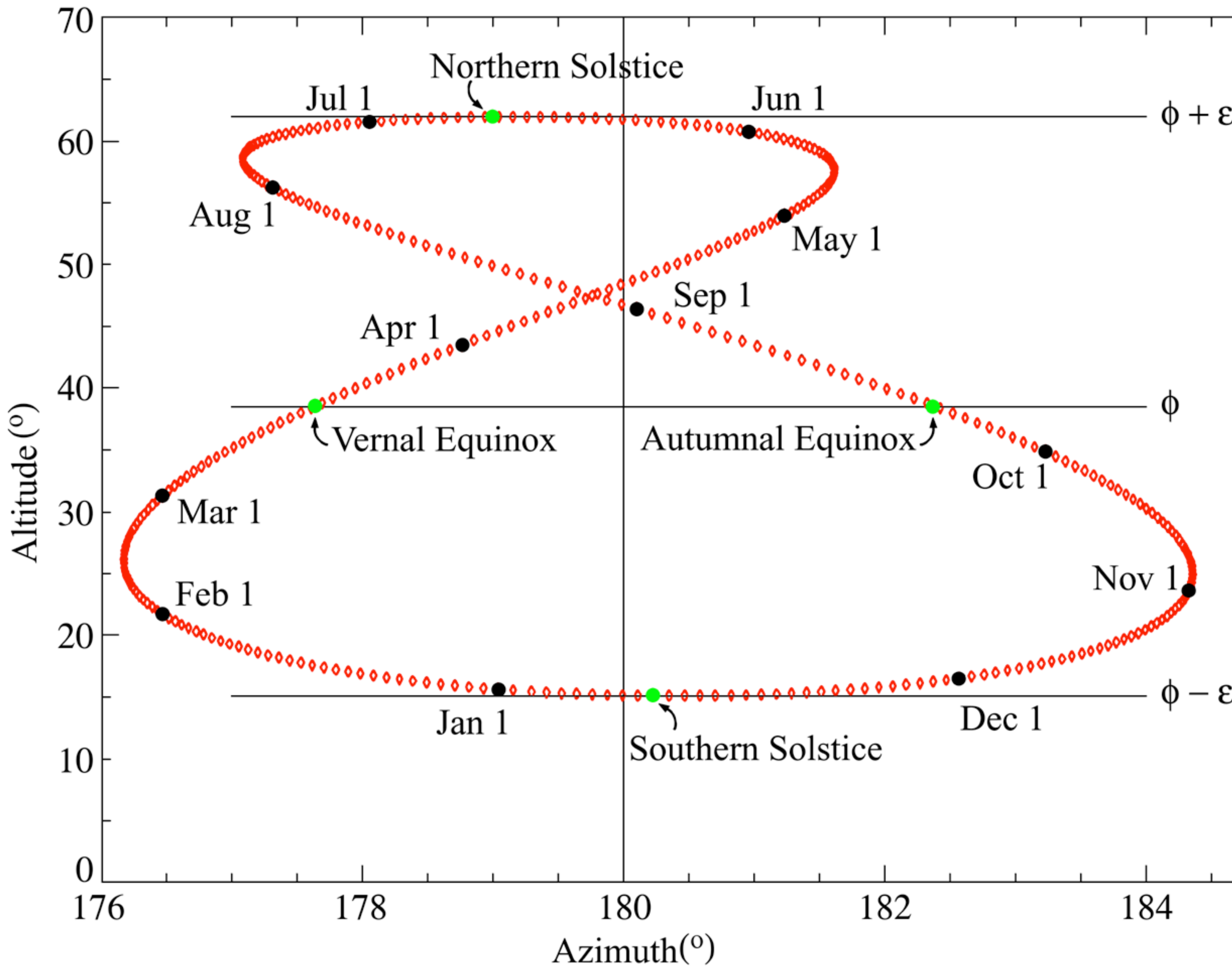
Technical definition:

A diagram showing the position of the Sun in the sky as seen from a **fixed location** on Earth at the same mean solar time, over the course of a year.



Solar analemma from Sulmona, Italy

Analemma at **mean solar time** *noon* from Greenwich Royal Observatory

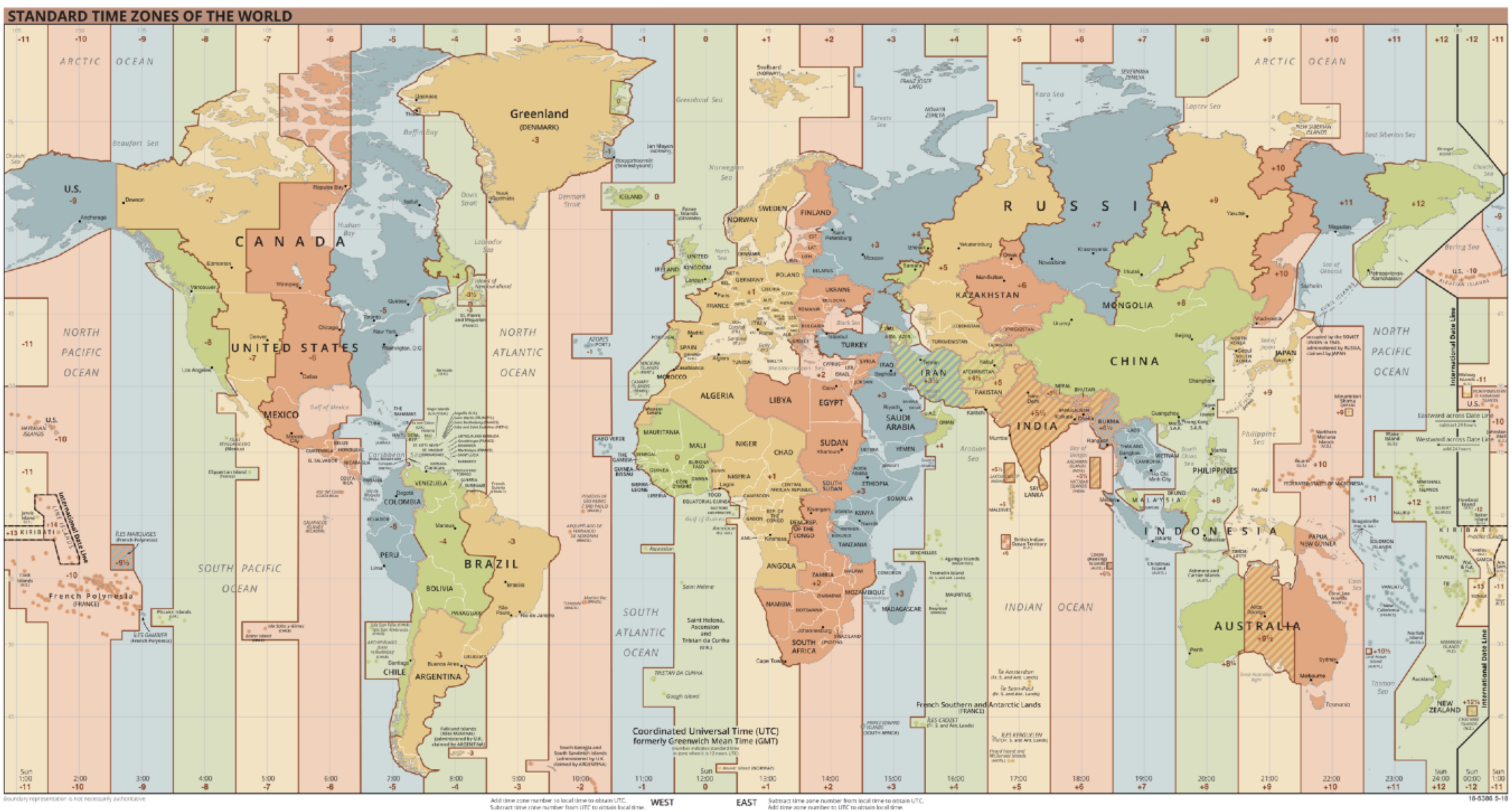


Simple Celestial Navigation with the Sun

- Measure the Sun's **altitude** when it transits the meridian. At that moment, the **apparent solar time** is 12:00PM.
- At that moment, use the chronometer onboard to look up the **mean solar time** at a known longitude (A): e.g., Greenwich
- Given the **date**:
  - Correct the 12:00PM Apparent Solar to Mean Solar Time with the **Equation of Time**
  - Look up the **Declination** of the Sun from the **ephemeris**
- We can now calculate our current location (B):
  - $\lambda(B)-\lambda(A) = [MST(B) - MST(A)] \times 15 deg/hr$
  - $\varphi(B) = [90 - Altitude(Sun)] + Dec(Sun)$

What time do we use everyday? Standard Mean Solar Time at a Time Zone

- Mean solar time has a precise dependency on longitude, making it difficult to use (e.g., *Des Moines is 8 min [2 deg] behind IC*). So we all use **Standard Time**
- **UTC/UT** = mean solar time at Greenwich (0 deg longitude)
  EST, **CST**, MST, PST keeps the mean solar time at λ = 75, **90**, 105, 120 deg W
- **CT = CST + 1 hr (Daylight Saving)**, between March 12 and November 5.



Summary of Time Conversions

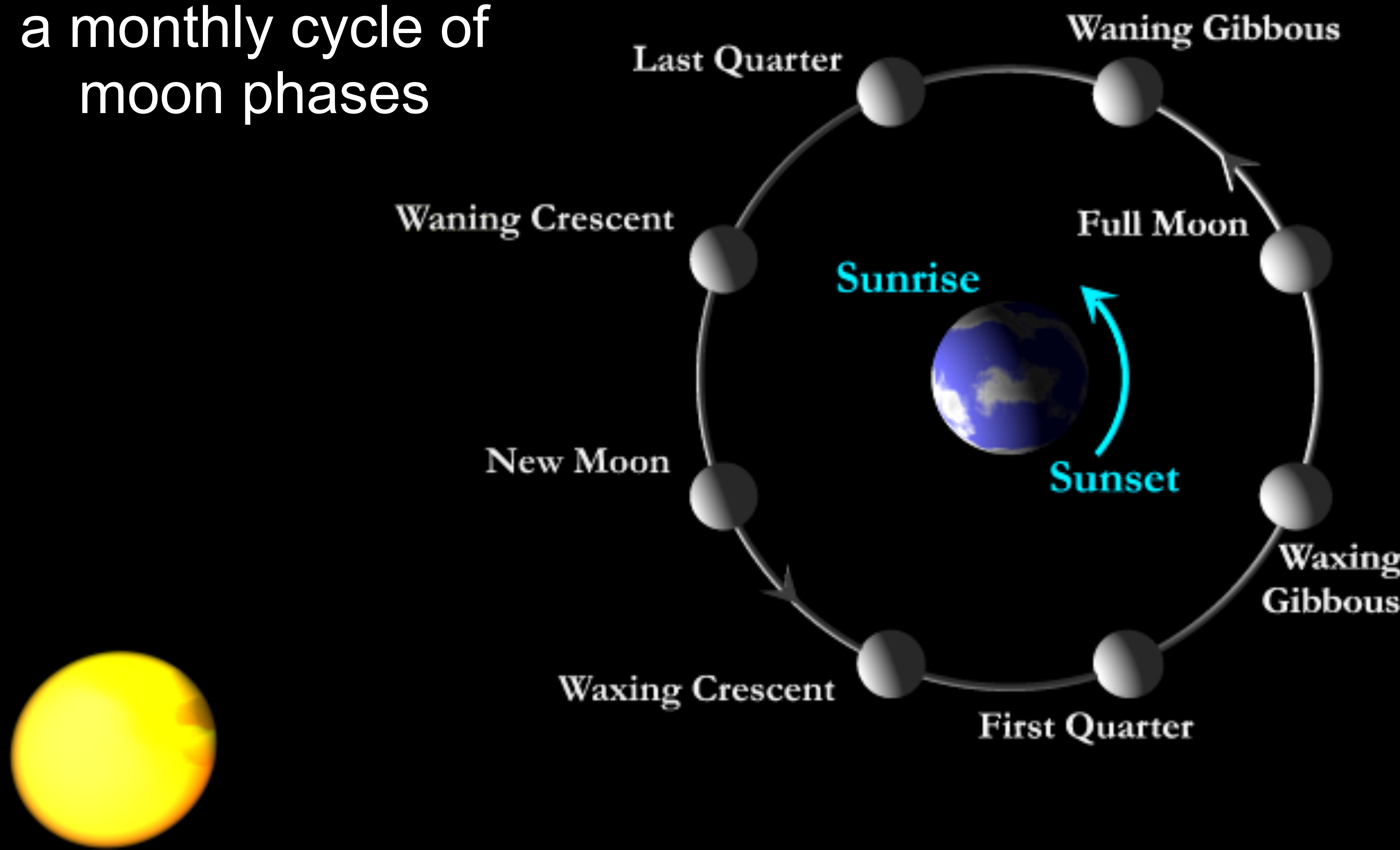
- **LST := $HA_{Ver.Eq.}$ = $RA_{Meridian}$**
- **AST := HA_{Sun} = LST - RA_{Sun} + 12h**
- **MST = AST - $(AST\text{-}MST)_{Date}$**
  [need to look up the Eq. of Time diagram]
- **MST - ST =** $(\lambda_{MST} - \lambda_{ST})/(15°/\text{hr})$
  [Western longitudes are negative]
- **UTC,** EST, **CST**, MST, PST, HST keeps the MST at λ = **0°**, 75°W, **90°W**, 105°W, 120°W, 150°W
- e.g., **CST = UTC - 6hr**,
  because 90°W means 6 hrs behind

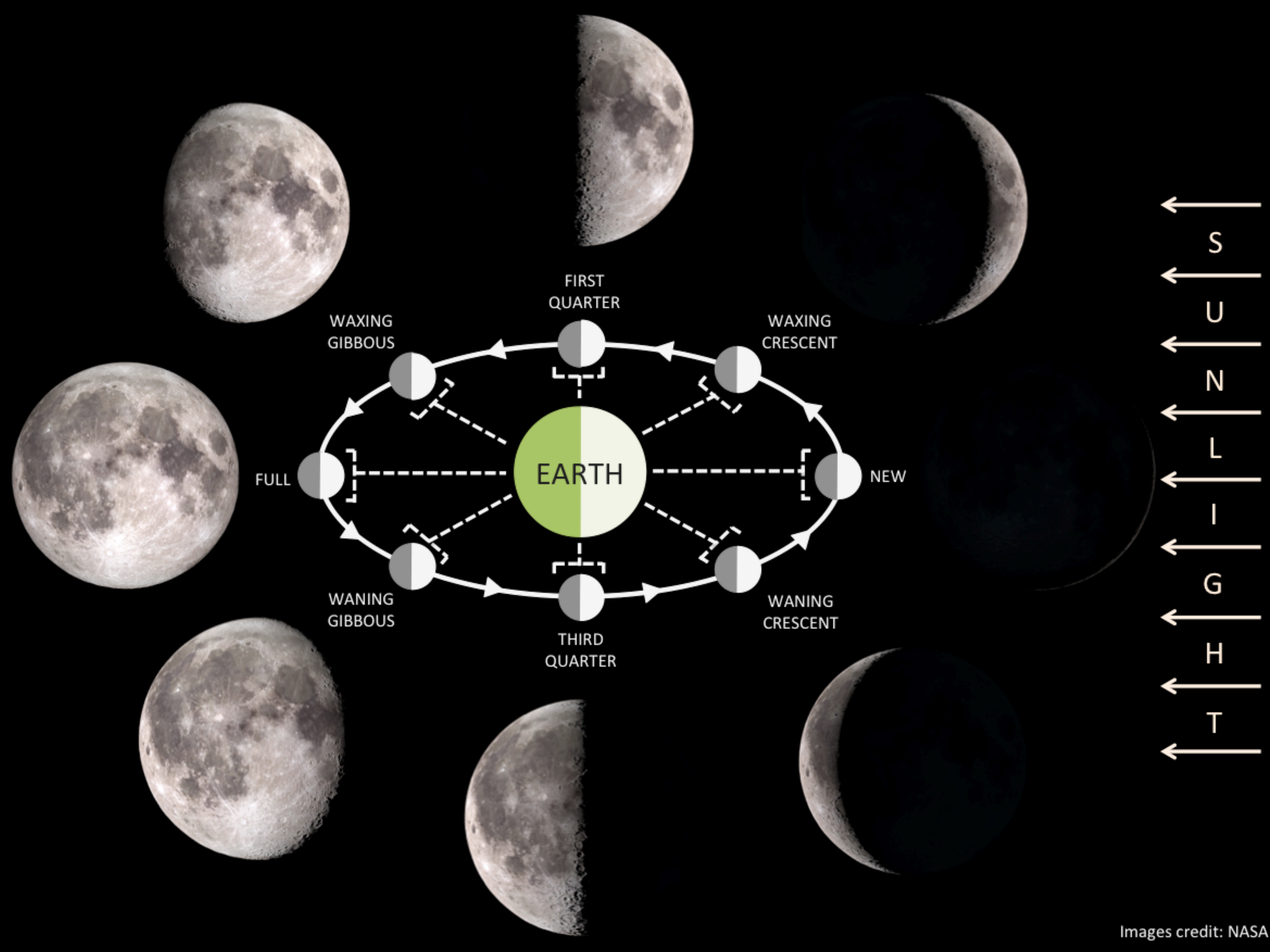
Motions of the Moon

Teotihuacán - Pyramid of the Moon, near Mexico City, built around 100 AD

Phases of the Moon due to its orbit around Earth

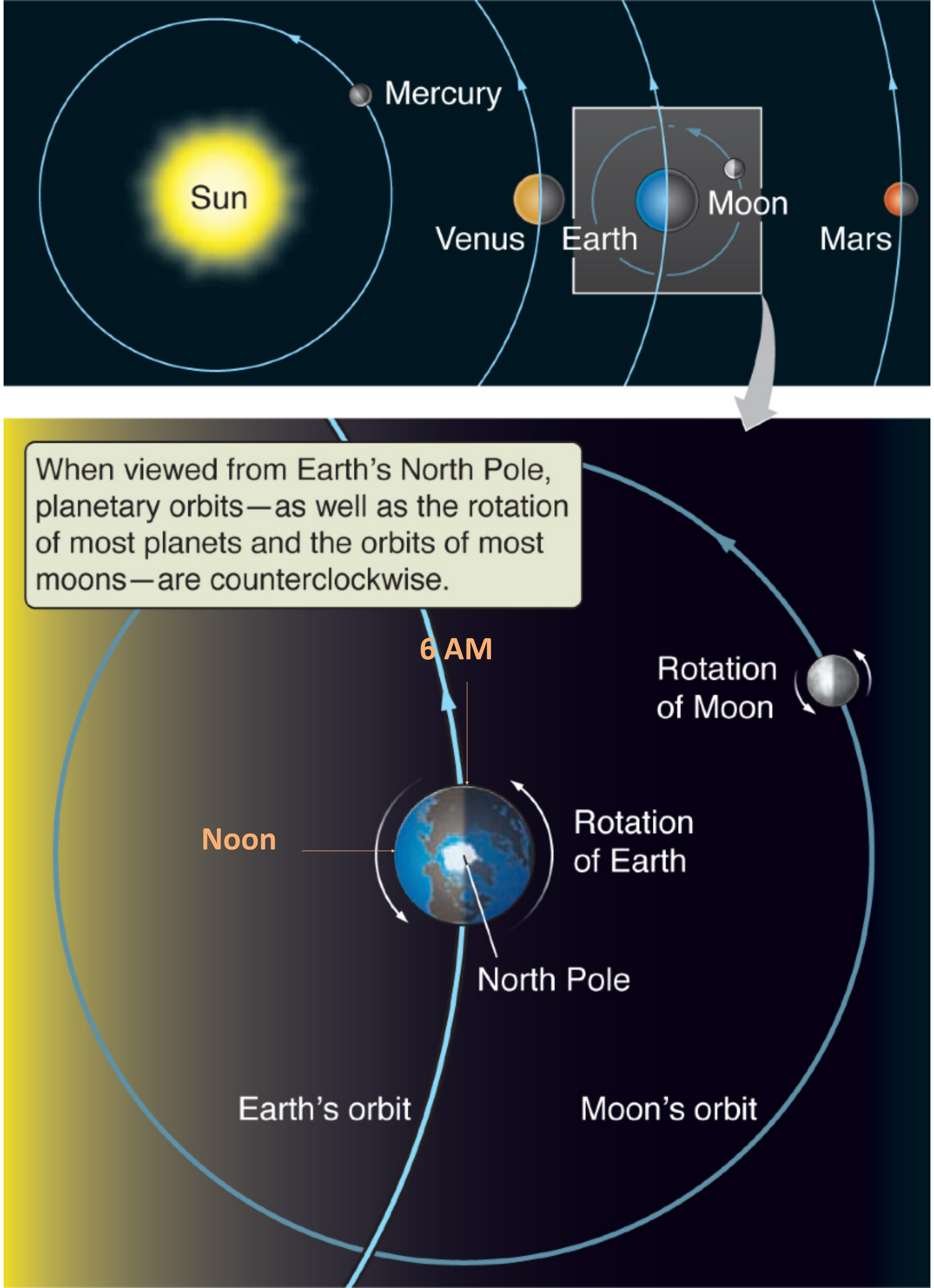
The monthly orbit of the moon causes a monthly cycle of moon phases




FIRST
QUARTER
WAXING
GIBBOUS
WAXING
CRESCENT
FULL
EARTH
NEW
WANING
GIBBOUS
WANING
CRESCENT
THIRD
QUARTER
SUNLIGHT
Images credit: NASA

Moon Phases fast-forwarded

Moon Phase Diagram



This diagram sets the observer above the **ecliptic north pole**, *ignoring* the 23.5° obliquity. From this angle, everything moves **counterclockwise**:

- Earth spins on its axis counterclockwise
- The orbit of the Earth around the Sun goes counterclockwise
- The orbit of the Moon around the Earth goes counterclockwise

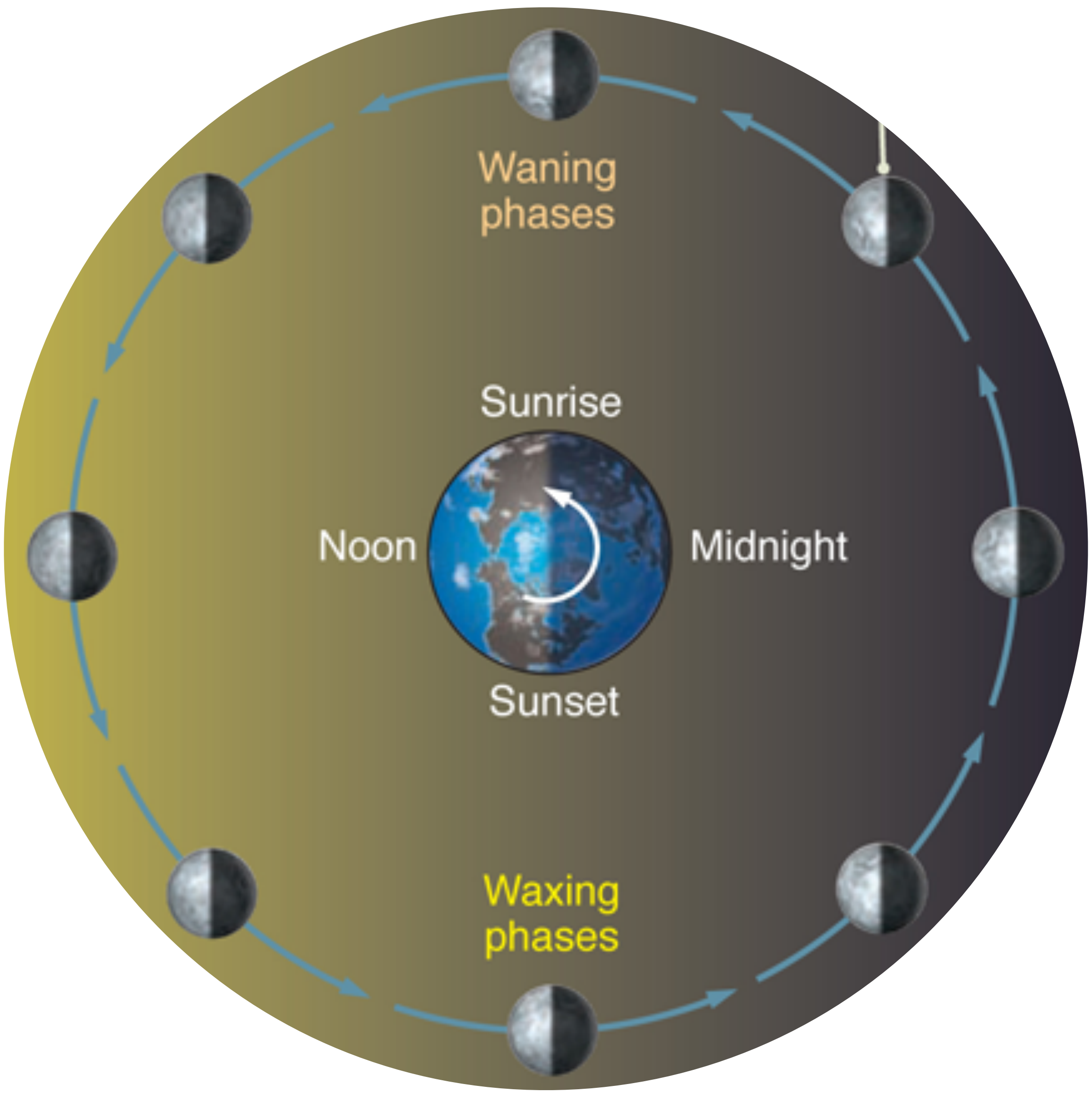
Part 1: Earth's Spin and Apparent Solar Time

The Sun

The Earth

Sunrise ~ 6AM | Noon ~ 12PM | Sunset ~ 6PM | Midnight ~ 12AM

Part 2: The orbit of the Moon and moon phases

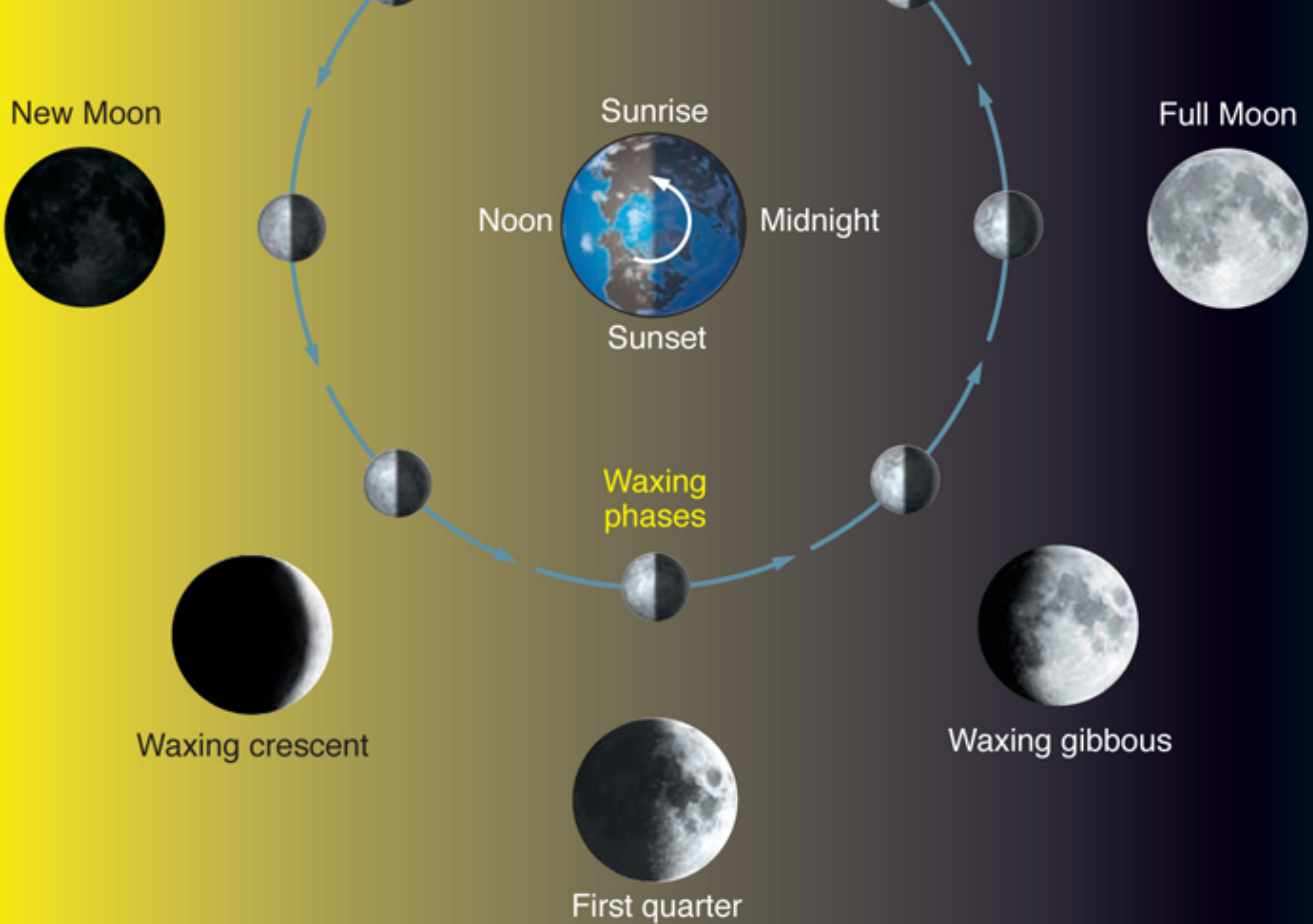


Chose eight representative positions along a orbit of the Moon.

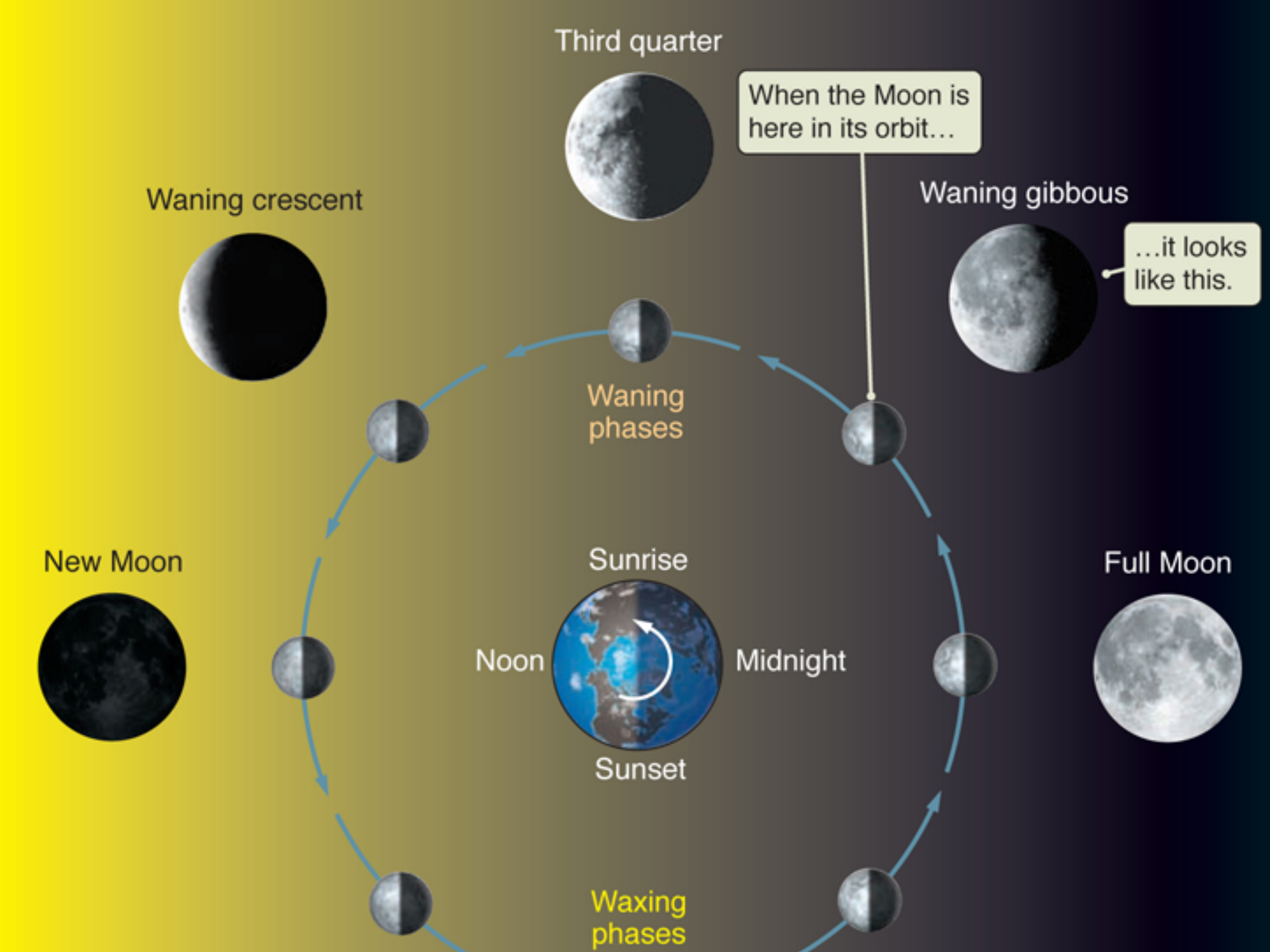
These 8 positions represent 8 different moon phases because their Sun-Moon-Earth angles are different.

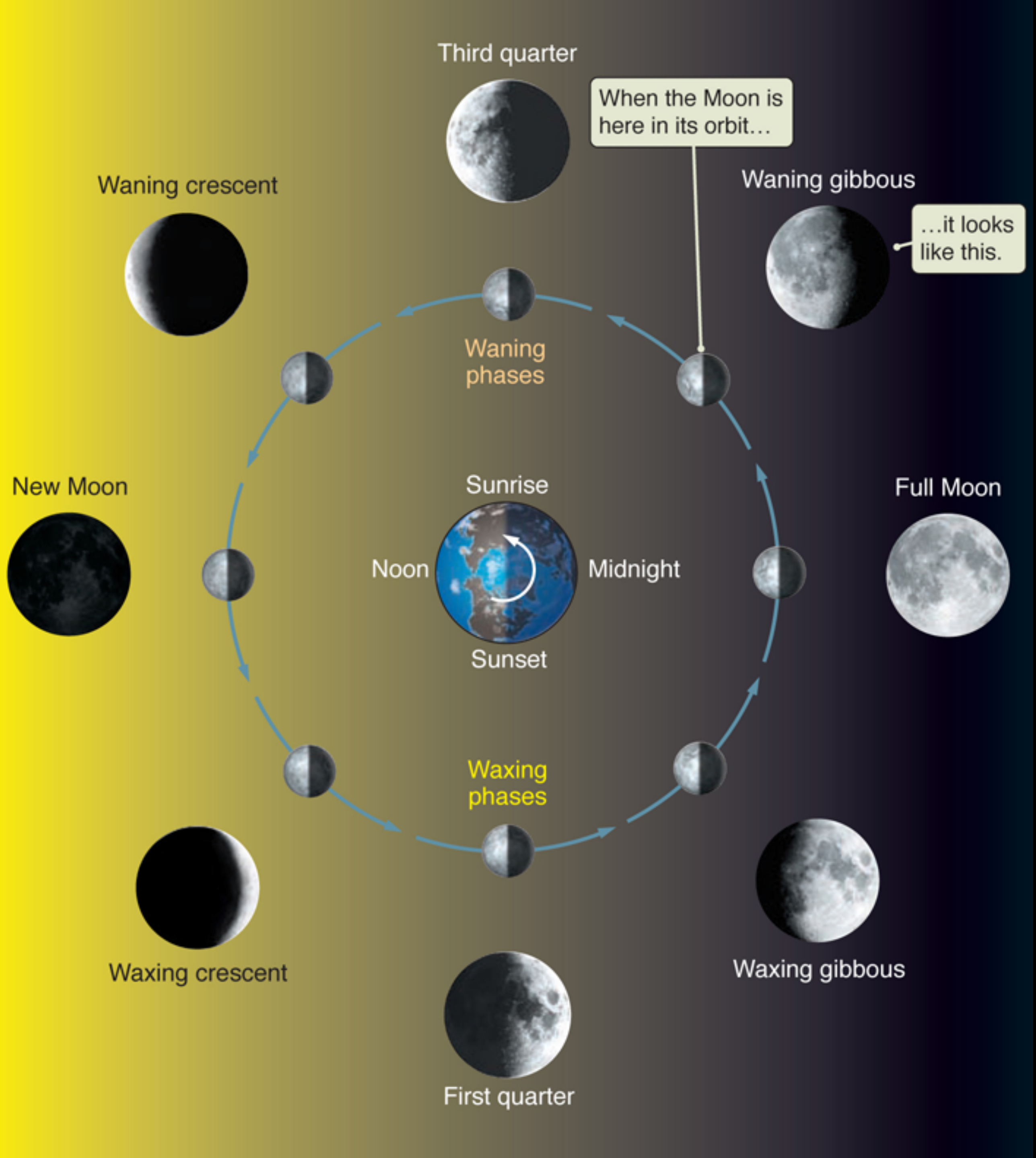
Note that the moon moves just slightly in an Earth day.

Part 3: The appearance of the Moon from Earth at each moon phase



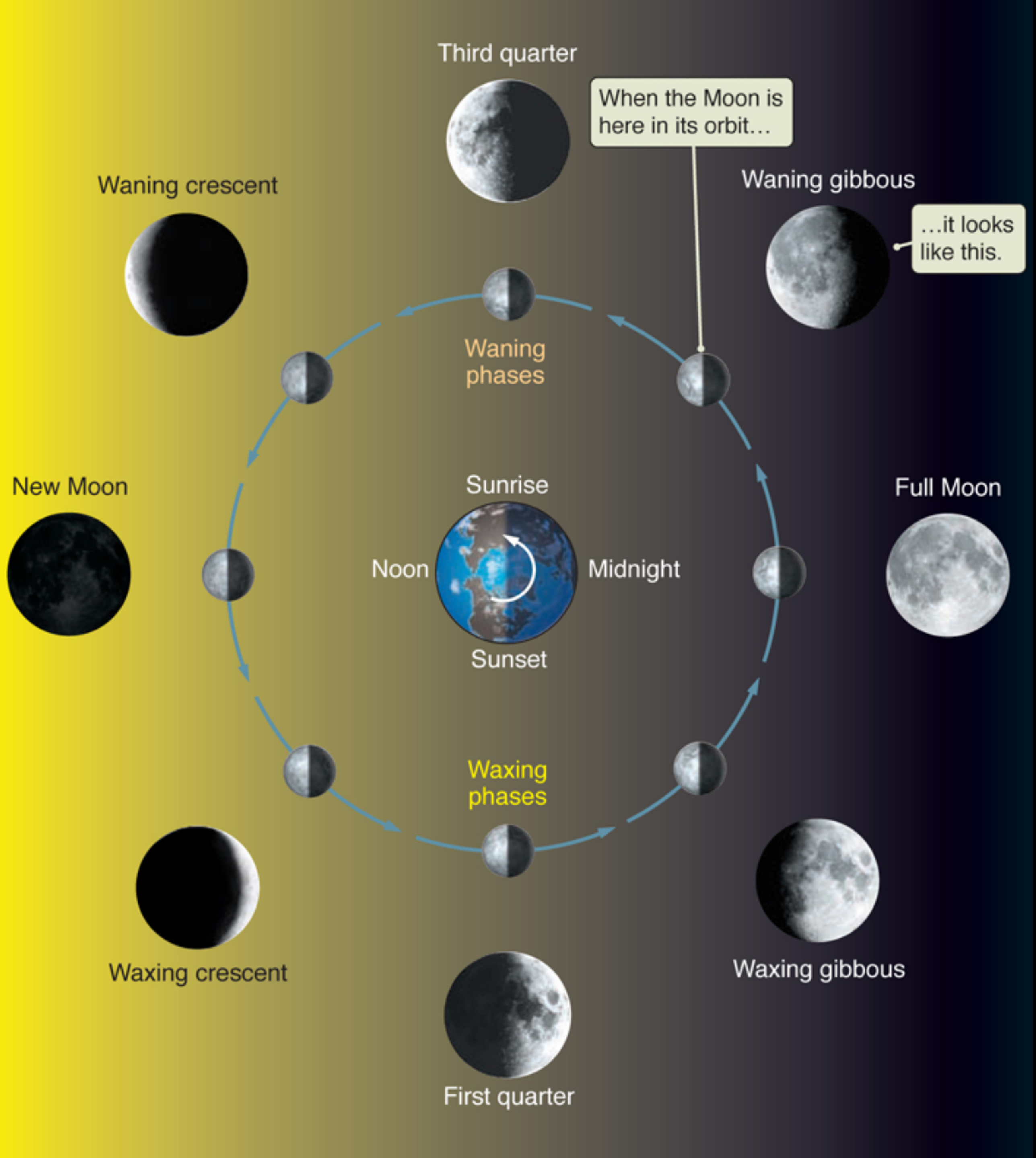
Phases: the appearances of the Moon at the eight phases


Third quarter
When the Moon is here in its orbit…
Waning crescent
Waning gibbous
…it looks like this.
Waning phases
New Moon
Sunrise
Full Moon
Noon
Midnight
Sunset
Waxing phases



Moon Phase Diagram

- *Apparent Solar Time*
- *Orbit of the Moon*
- *Appearance of the moon at 8 equally spaced positions in the orbit*
- *Names of the moon phases*



Moon Phase Diagram

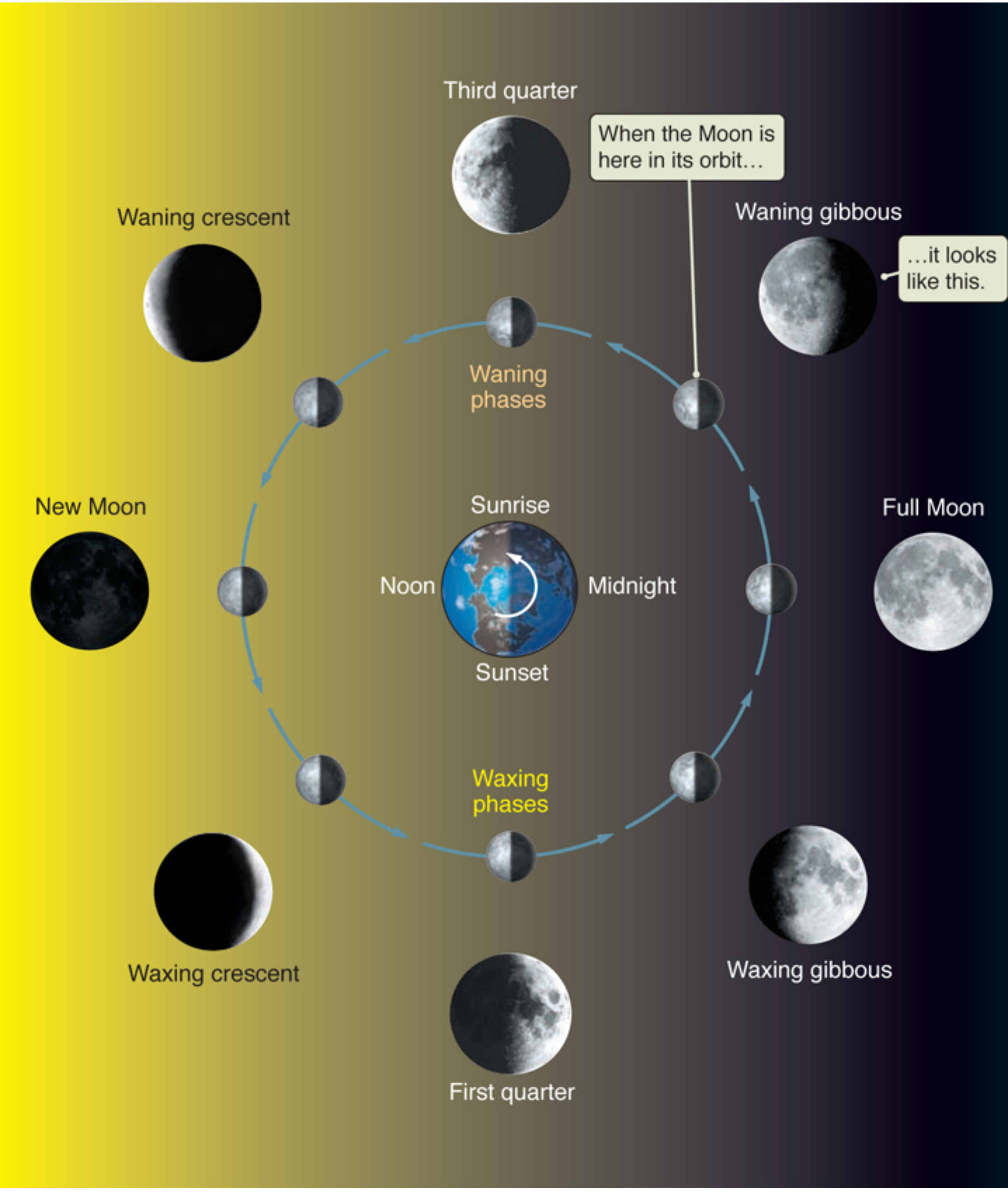
- *New Moon*
- *Waxing crescent*
- *First Quarter*
- *Waxing gibbous*
- *Full Moon*
- *Waning gibbous*
- *Third quarter*
- *Waning crescent*

Which phase is the Moon in?

A. First quarter
B. Waxing gibbous
C. Waning gibbous
D. Third quarter
E. Waxing crescent

How to estimate apparent solar time from Moon phases?

Suppose today's moon phase is full, when'll it rise from the horizon?

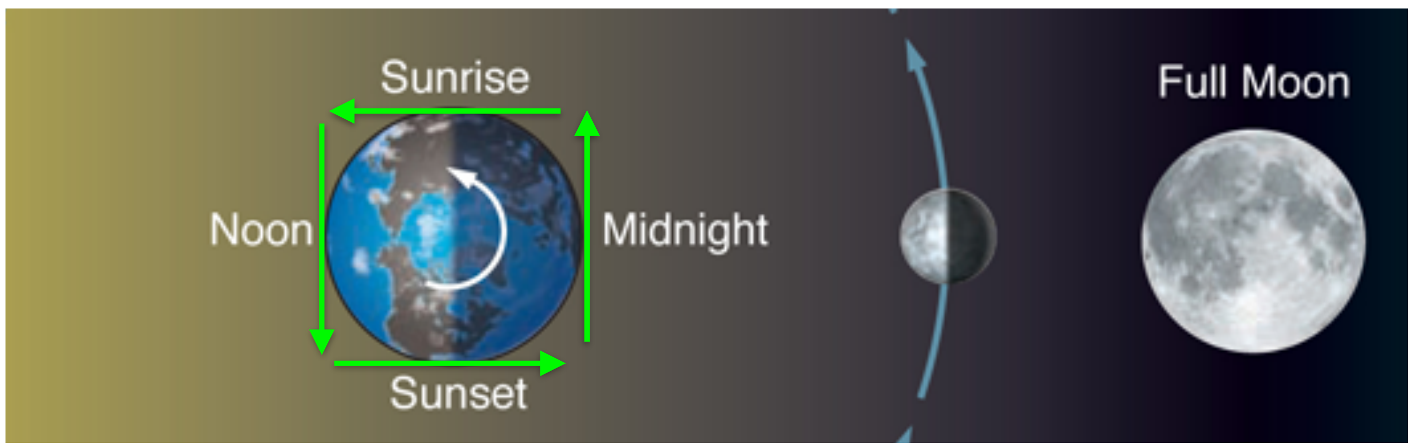


How to estimate the apparent solar time when a given-phase moon rises, transits, and sets? For example, the full moon.

Note 1: Everywhere in the world sees the same moon phase, so for simplicity, just imagine yourself on the equator.

Note 2: This diagram is not to scale, and the moon is very far away than it appears on this diagram (no significant parallax)

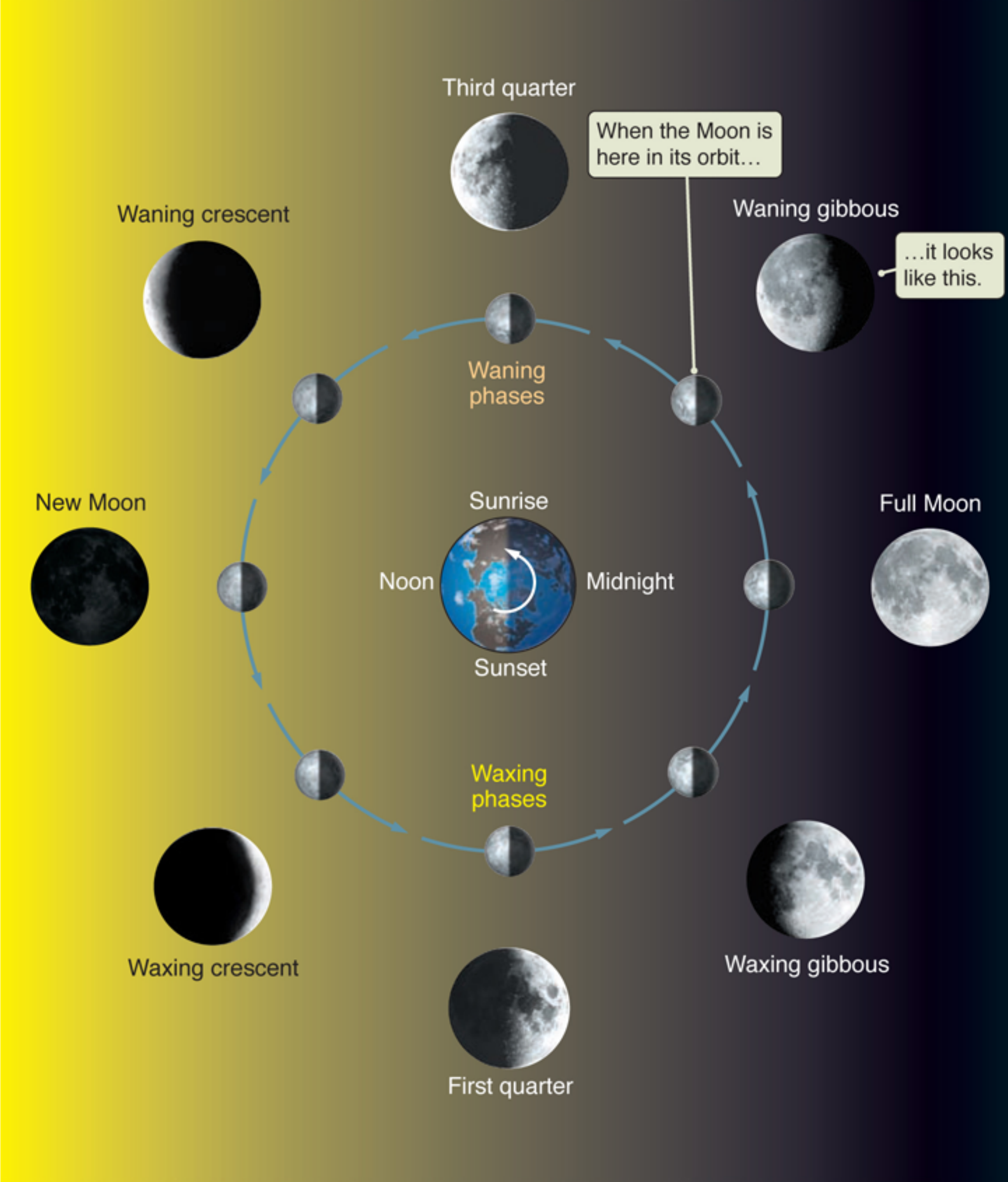
Direction to the Sun



Sunrise ~ 6AM | Noon ~ 12PM | Sunset ~ 6PM | Midnight ~ 12AM

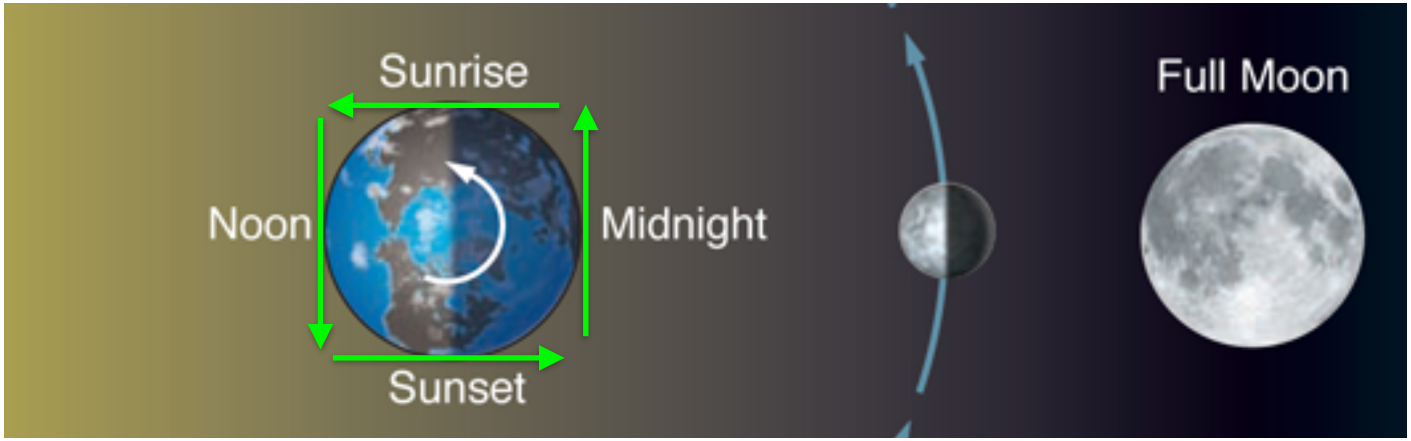
Draw green arrows that indicate the horizon at each time and use its direction to point at the east

When will a full moon rise?



When will the full moon rise?

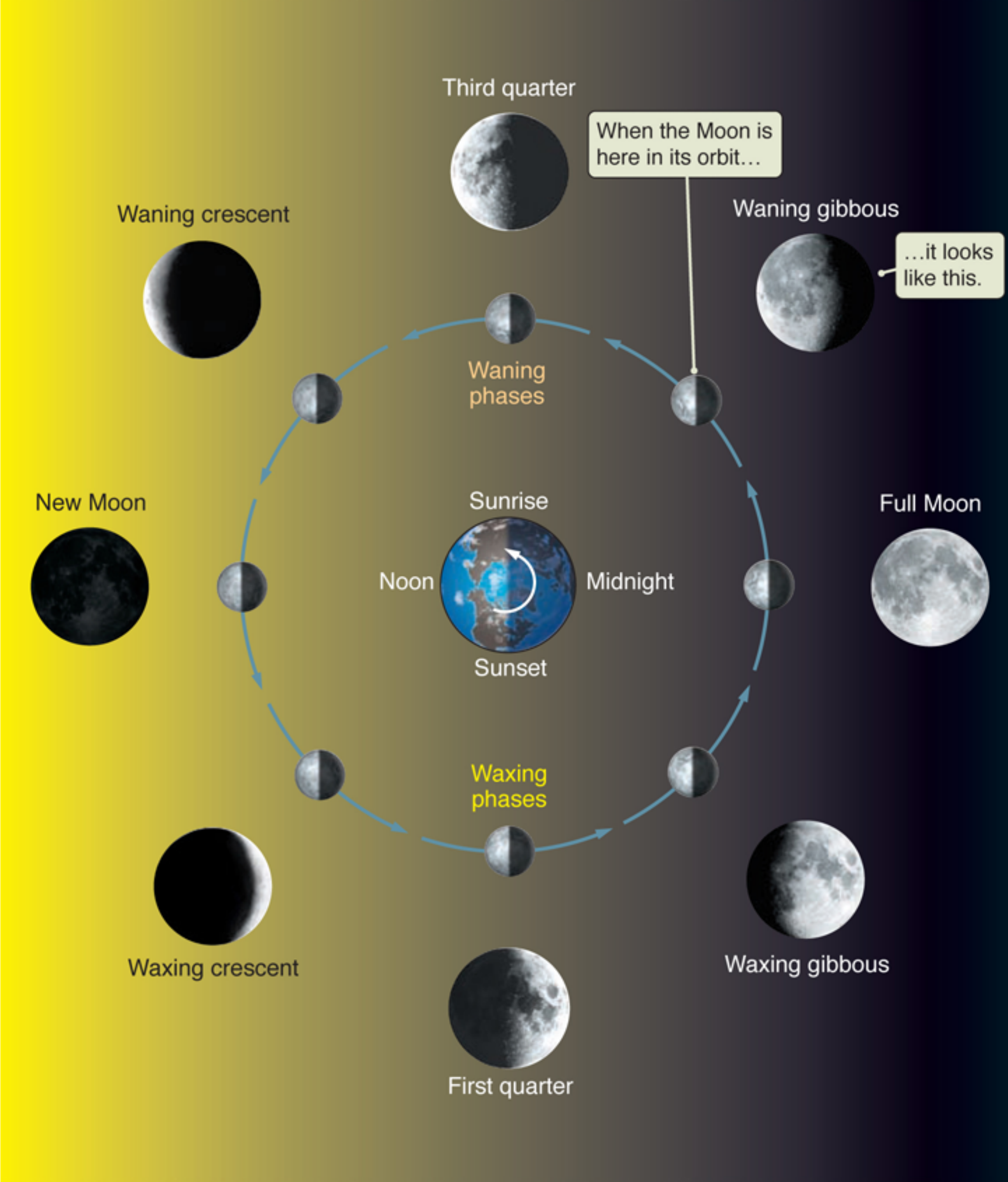
Direction to the Sun



Sunrise ~ 6AM | Noon ~ 12PM | Sunset ~ 6PM | Midnight ~ 12AM

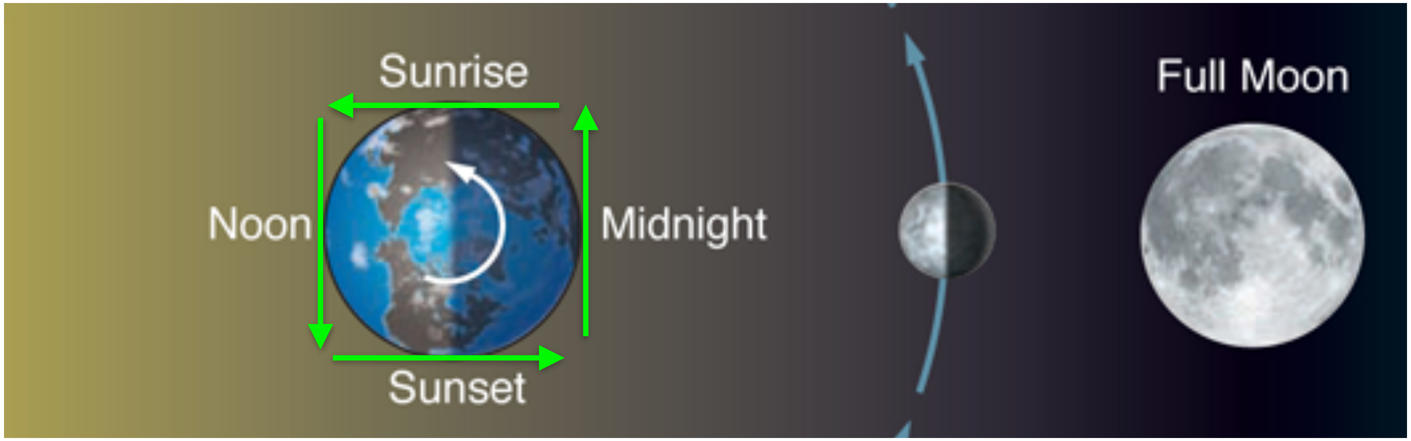
Draw green arrows that indicate the horizon at each time and use its direction to point at the east

You saw a full moon directly to the South, what time is it?



When will the full moon transit?

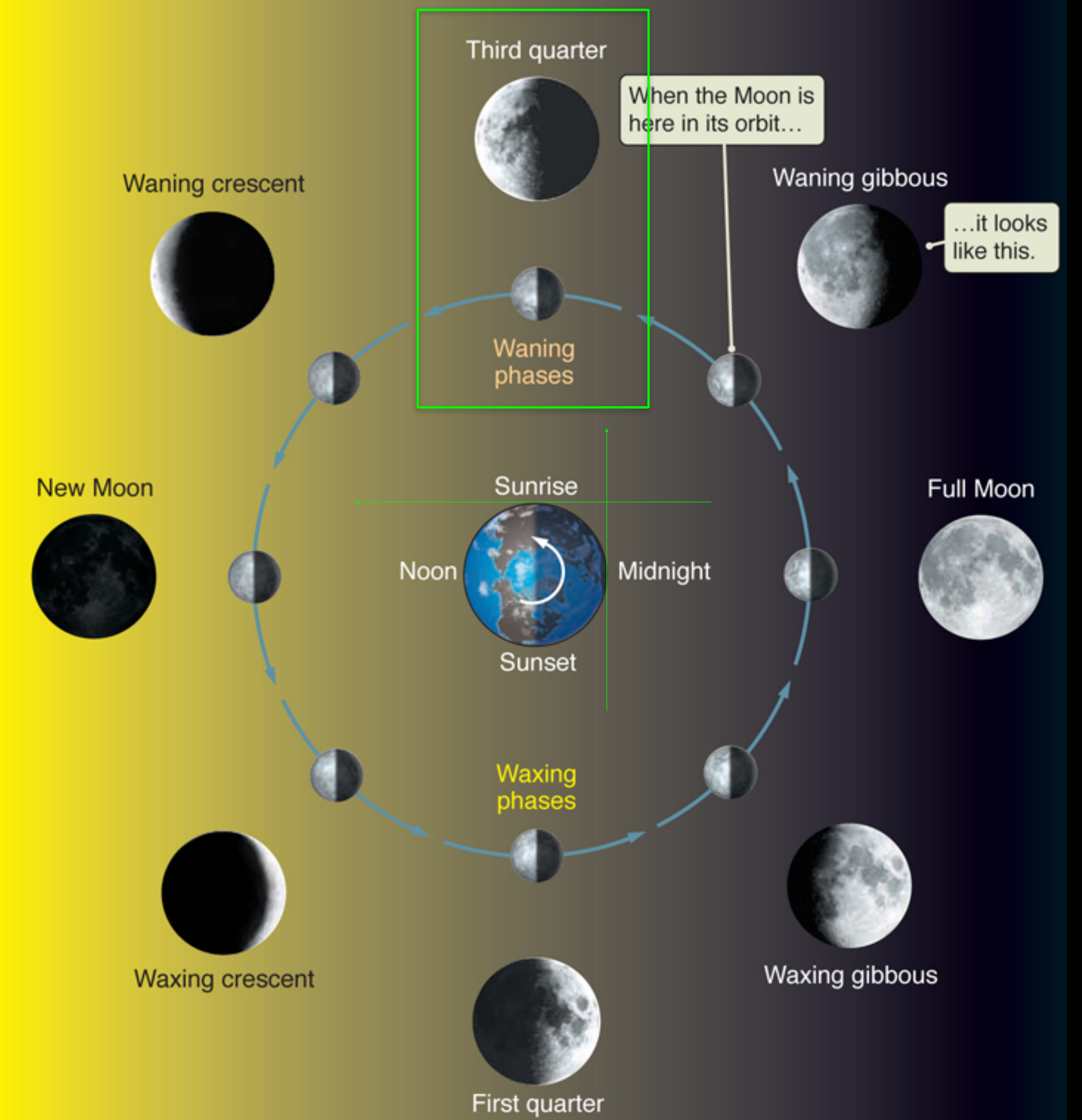
The Sun



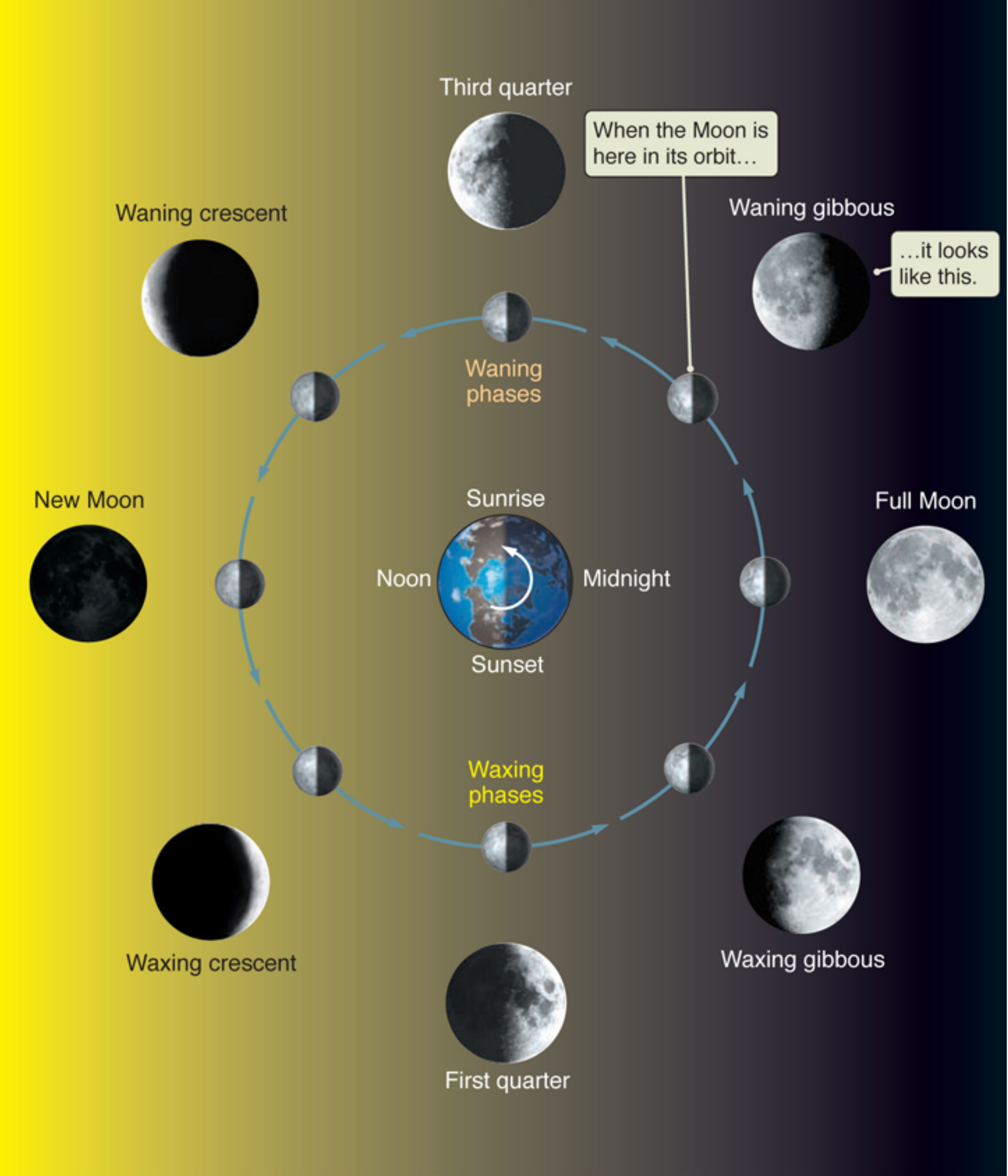
Sunrise ~ 6AM | Noon ~ 12PM | Sunset ~ 6PM | Midnight ~ 12AM

Draw green arrows that indicate the horizon at each time and use its direction to point at the east

When will a third quarter moon rise (from the horizon)?



You see a third quarter moon directly to the South, what time is it?



Earth's Fine Motions & Climate Change
(a quick 15 min intro)

The Last Ice Age: 115-12 kyrs ago

Maximum Ice Coverage: 26-20 kyrs ago

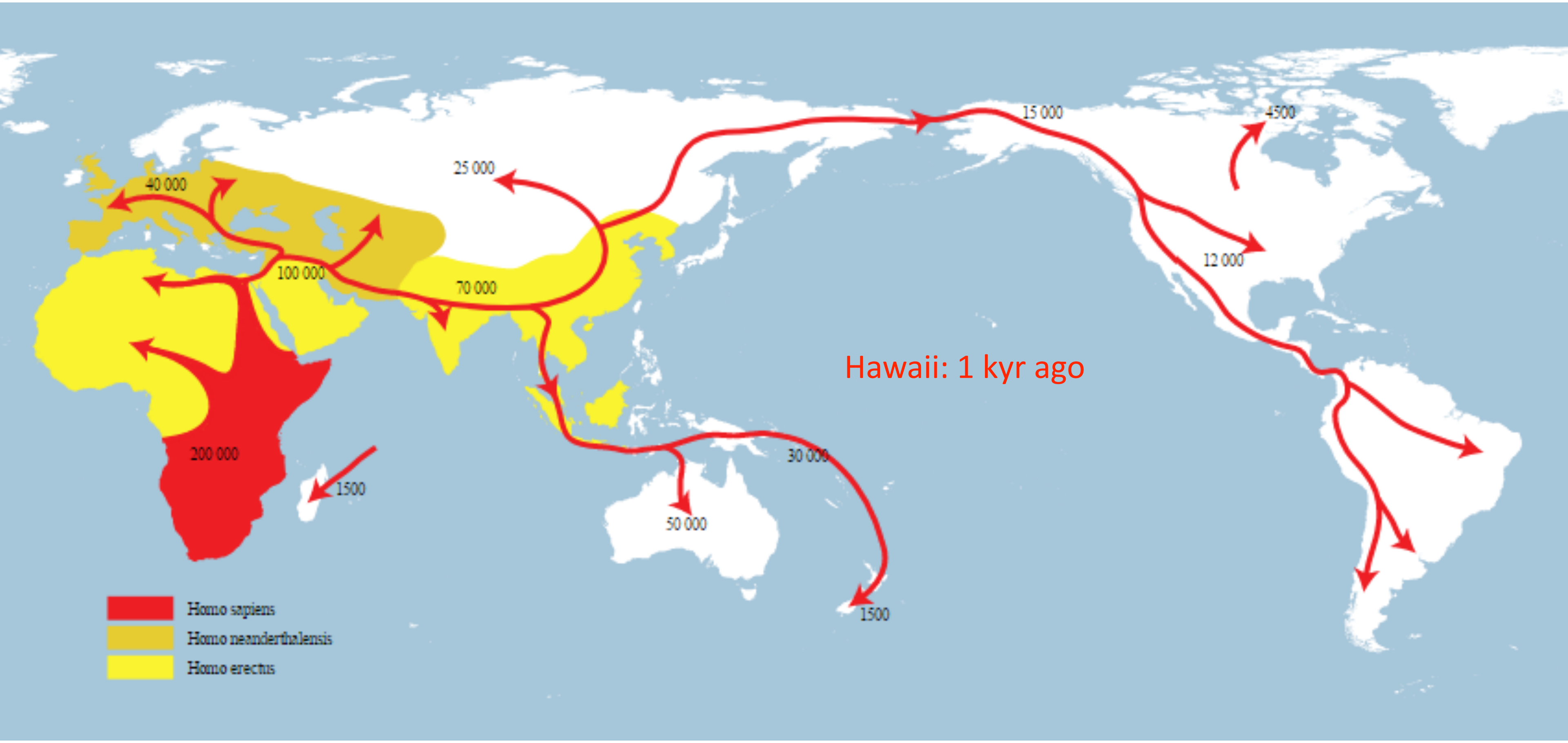
Ice covered all of Canada, down to Missouri

The Spread of *Homo Sapiens* across the Continents

The Last Glacial Period: 115 - 12 kyrs ago

Europe & Asia: 70 - 40 kyrs ago

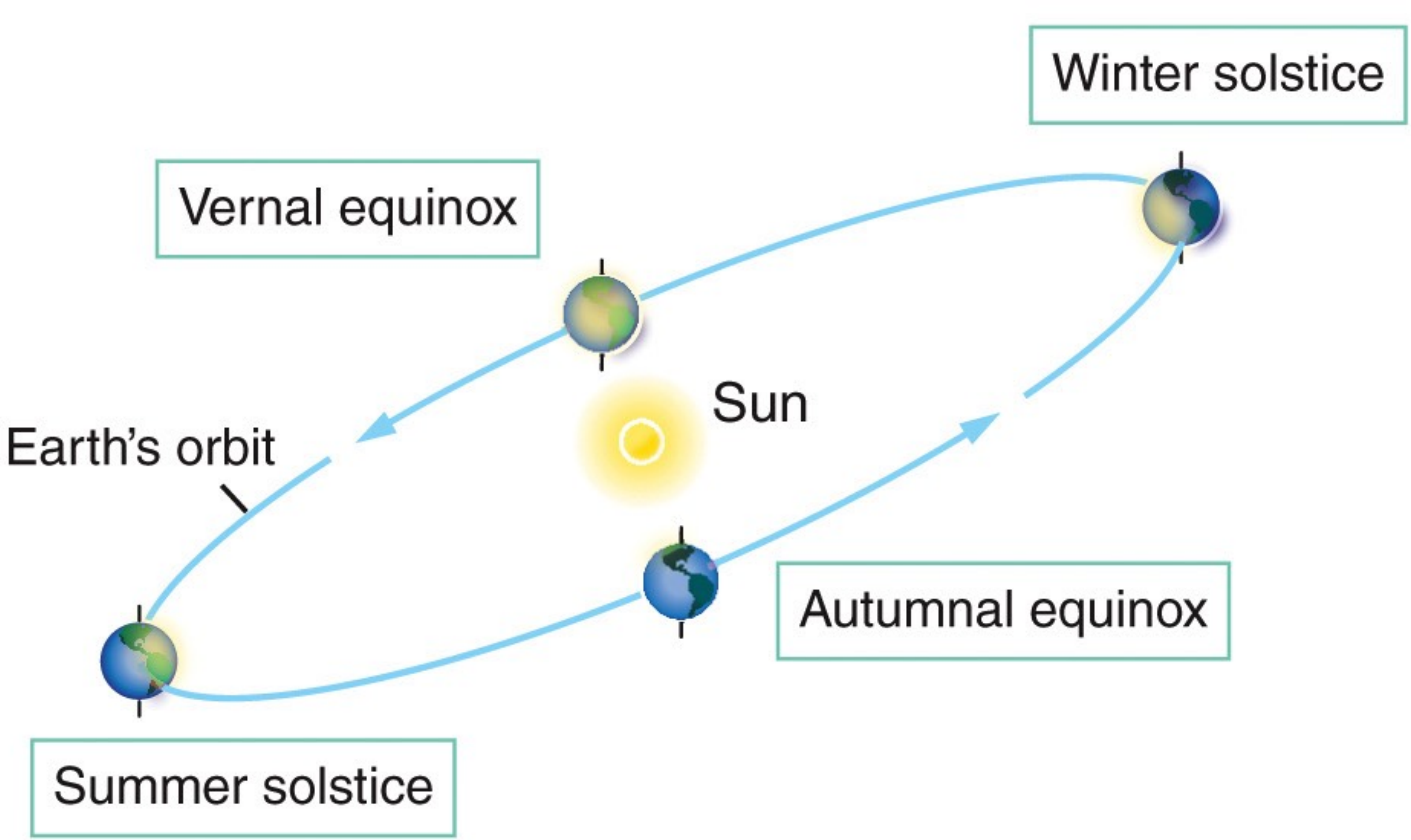
North America: 12 kyrs ago



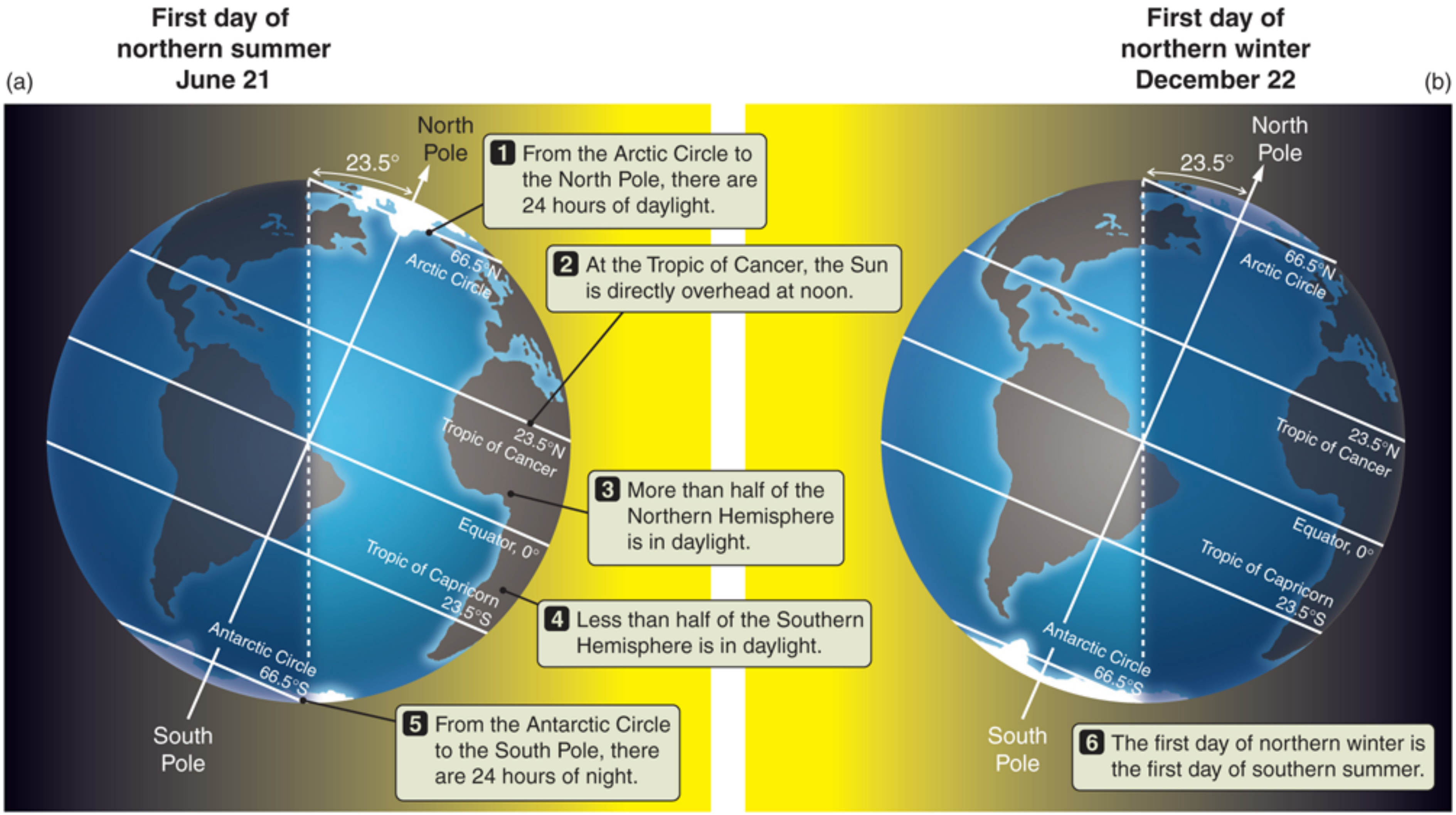
Australia: 50 kyrs ago

Short-term Cycles of Earth's Motions

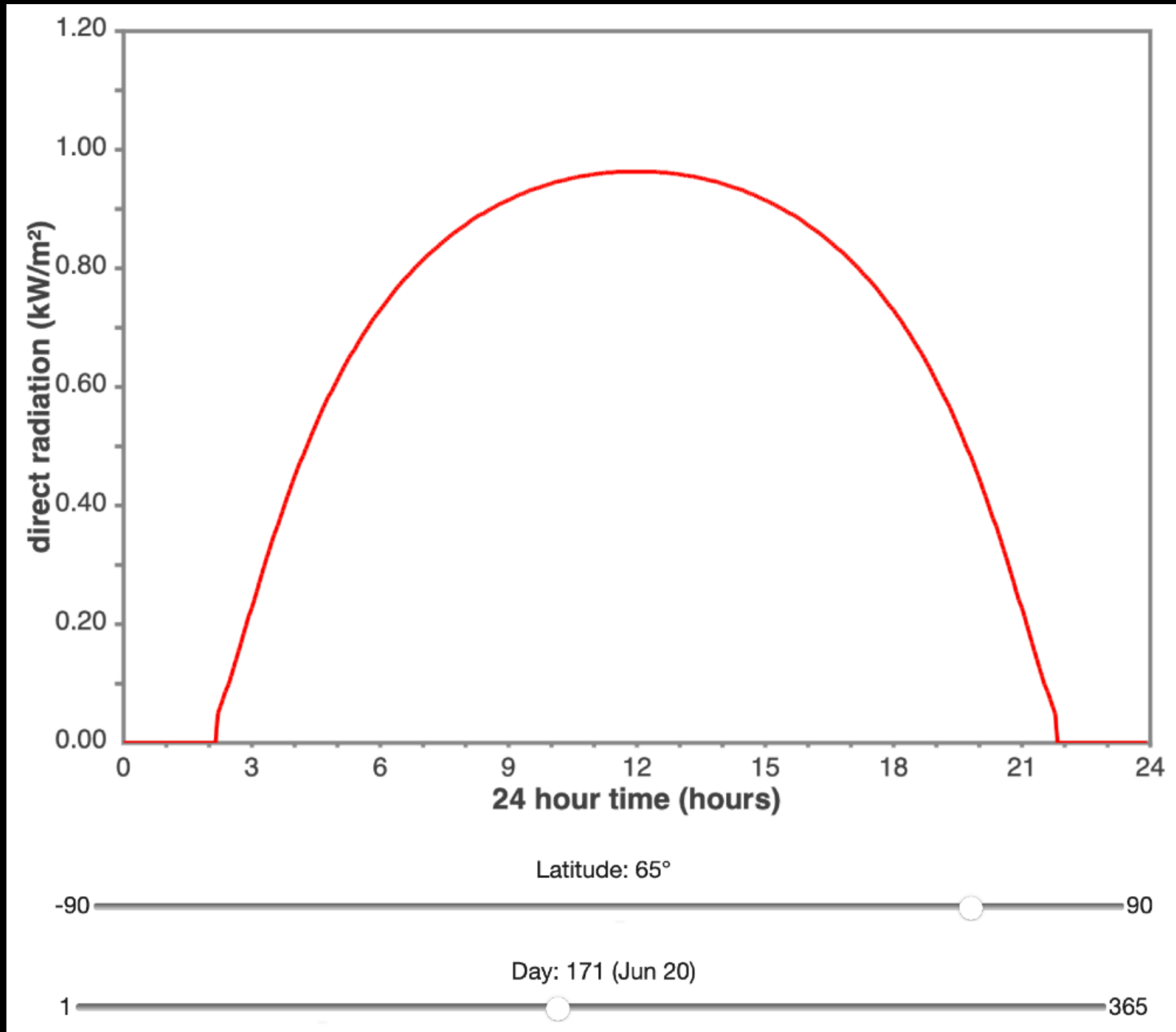
daily rotation & yearly revolution



Seasons caused by changes in solar isolation



Solar Insolation on Summer Solstice at 65°N



https://www.pveducation.org/pvcdrom/properties-of-sunlight/calculation-of-solar-insolation

Long-term Cycles of Earth's Motions

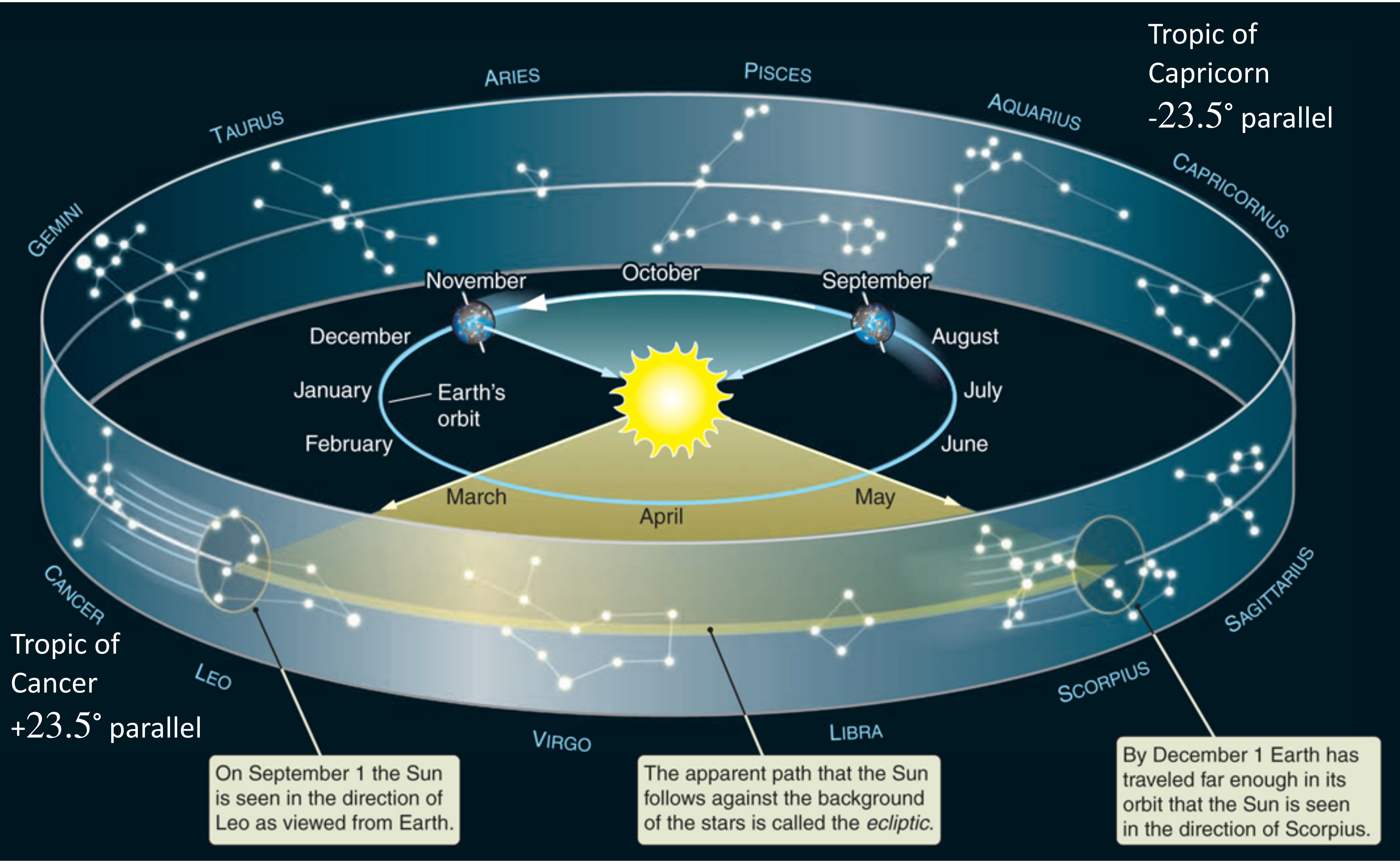
eccentricity, obliquity, precession

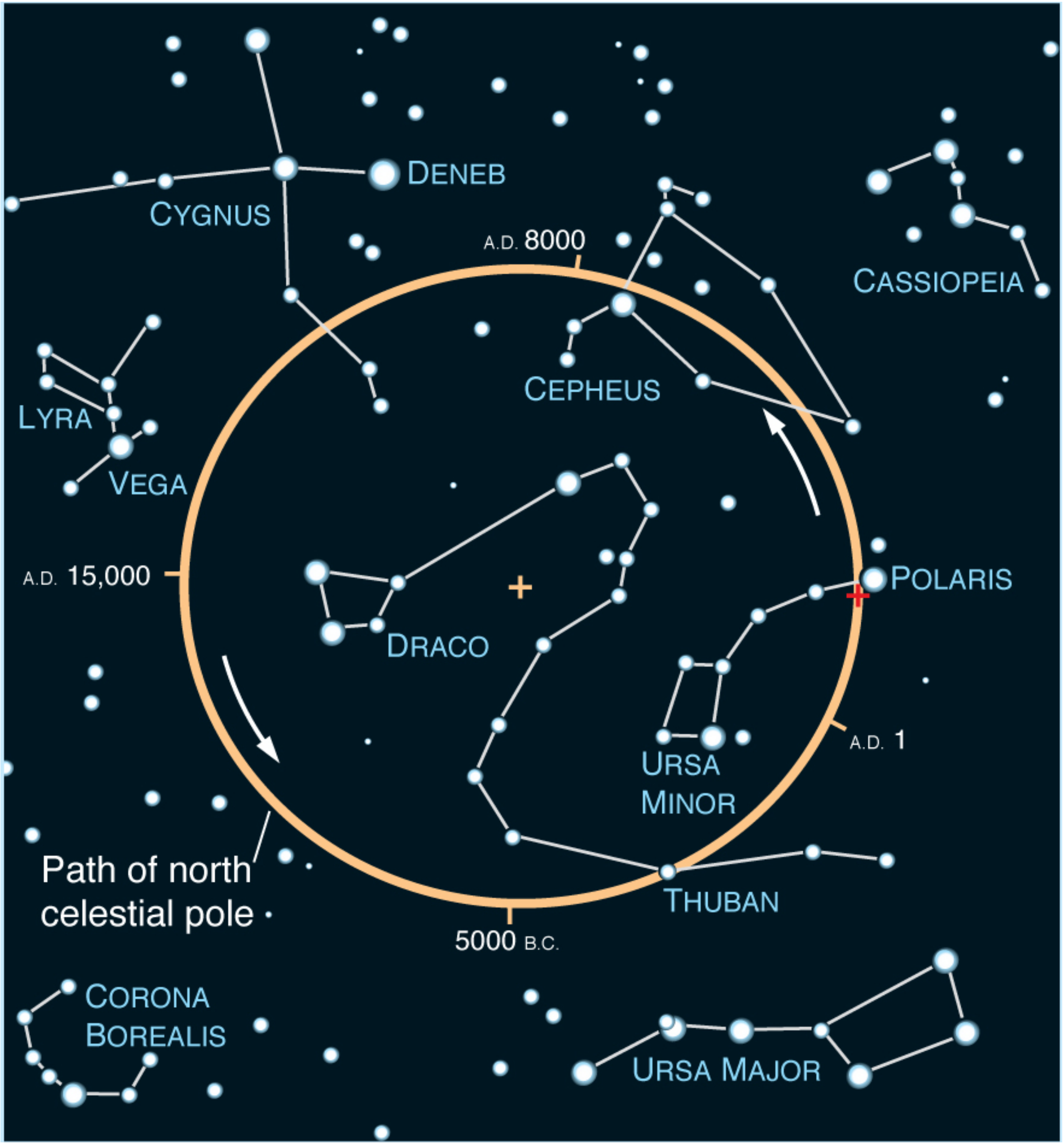
Axial Precession (Wobble)

26,000-year cycles

climate.nasa.gov

- Because of the Earth's precession, the location of the Vernal Equinox moves along the ecliptic, changing the celestial coordinates (R.A. & Dec) and messing up the zodiac of each month.
- Tropic of Cancer has now become Tropic of Taurus (the Sun's constellation on Summer Solstice),
- Tropic of Capricorn has now become Tropic of Sagittarius (the Sun's constellation on Winter Solstice)

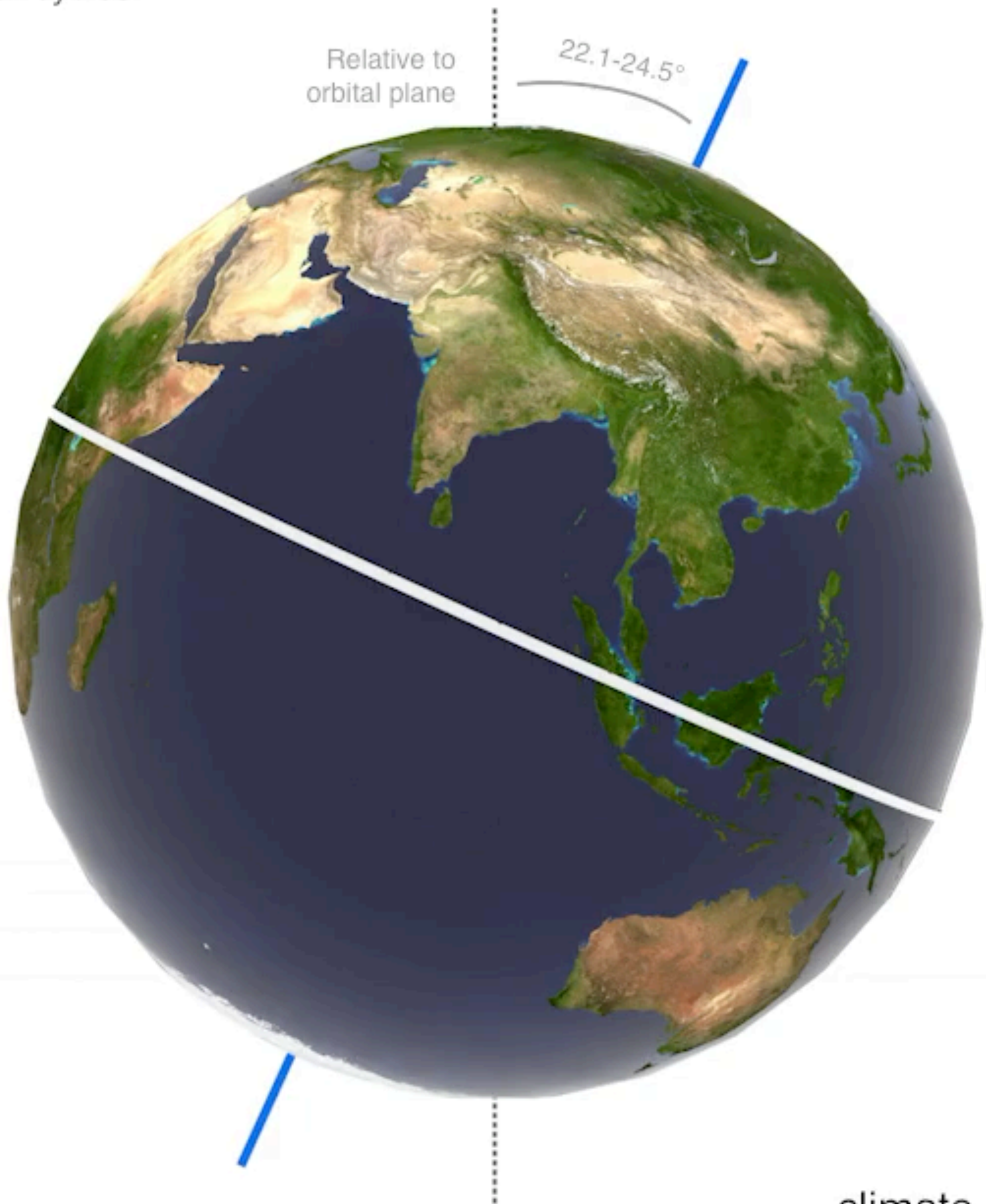




- Currently the north celestial pole is near the bright star Polaris.
- In 10000 years, it will be close to Vega.

Changes in Obliquity (Tilt)

41,000-year cycles



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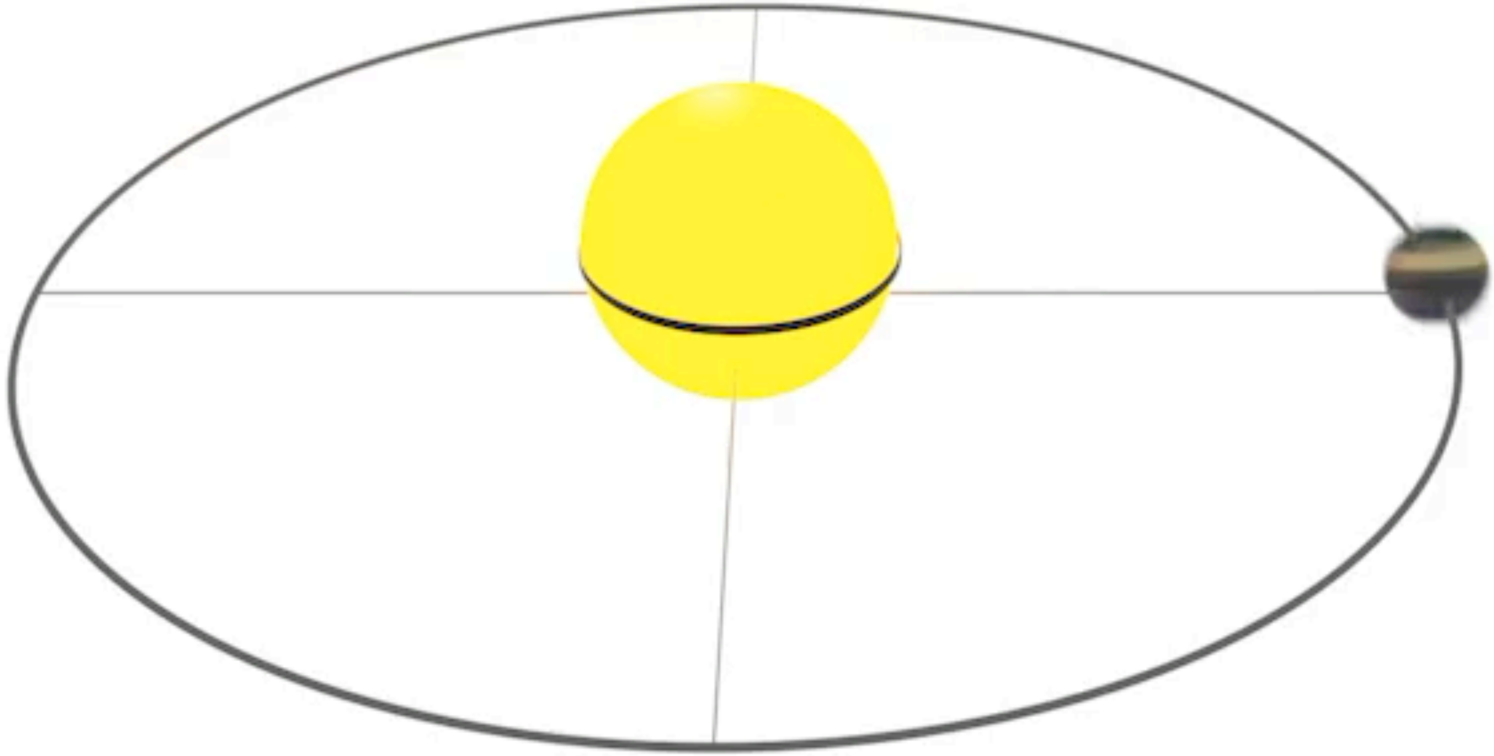
Changes in Eccentricity (Orbit Shape)

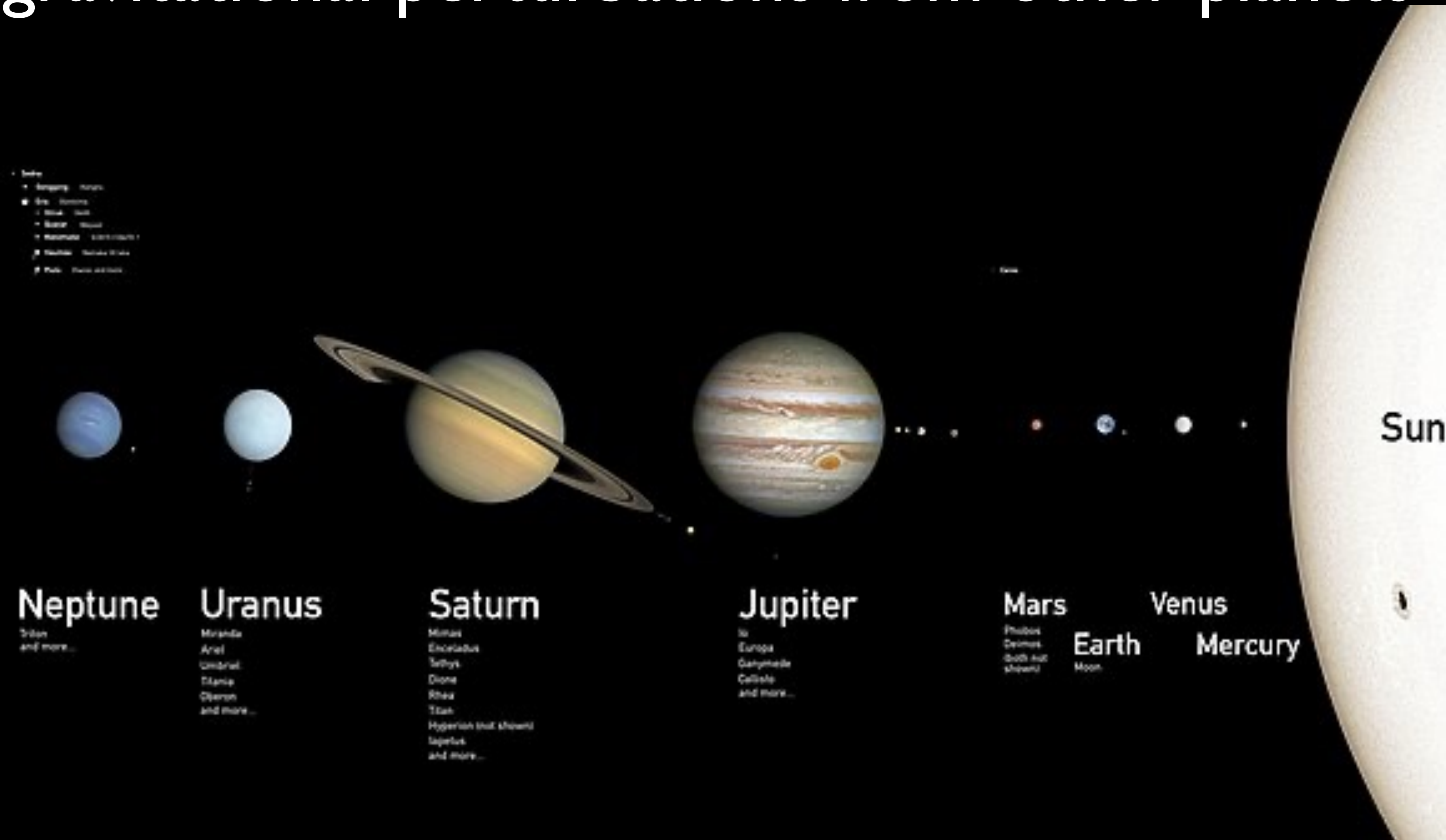
100,000-year cycles



*Changes in eccentricity exaggerated so the effect can be seen. Earth's orbit shape varies between 0.0034 (almost a perfect circle) to 0.058 (slightly elliptical).

climate.nasa.gov

Obliquity and eccentricity changes due to gravitational perturbations from other planets



Milankovitch Cycles & Ice Ages

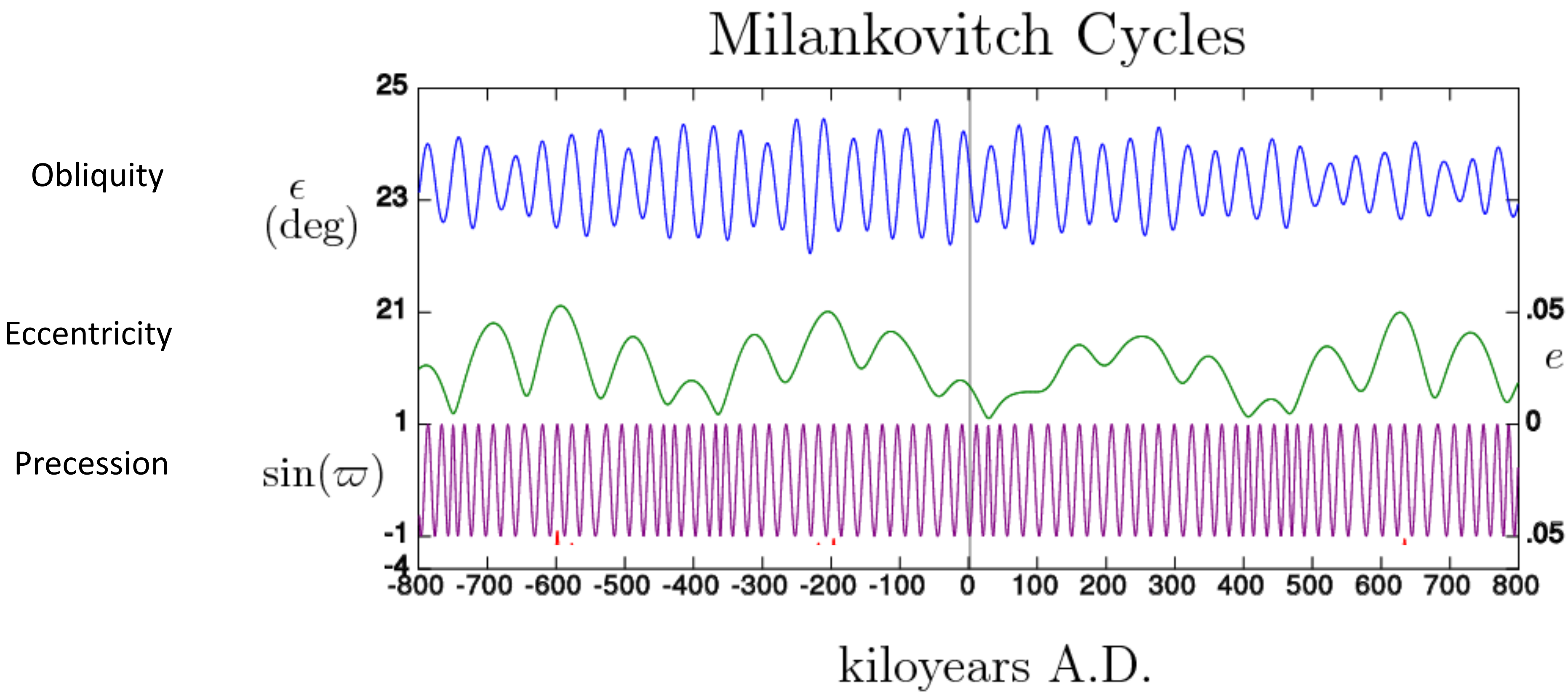
eccentricity, obliquity, precession

Milankovitch used changes in Earth's motion to explain its long-term climate changes

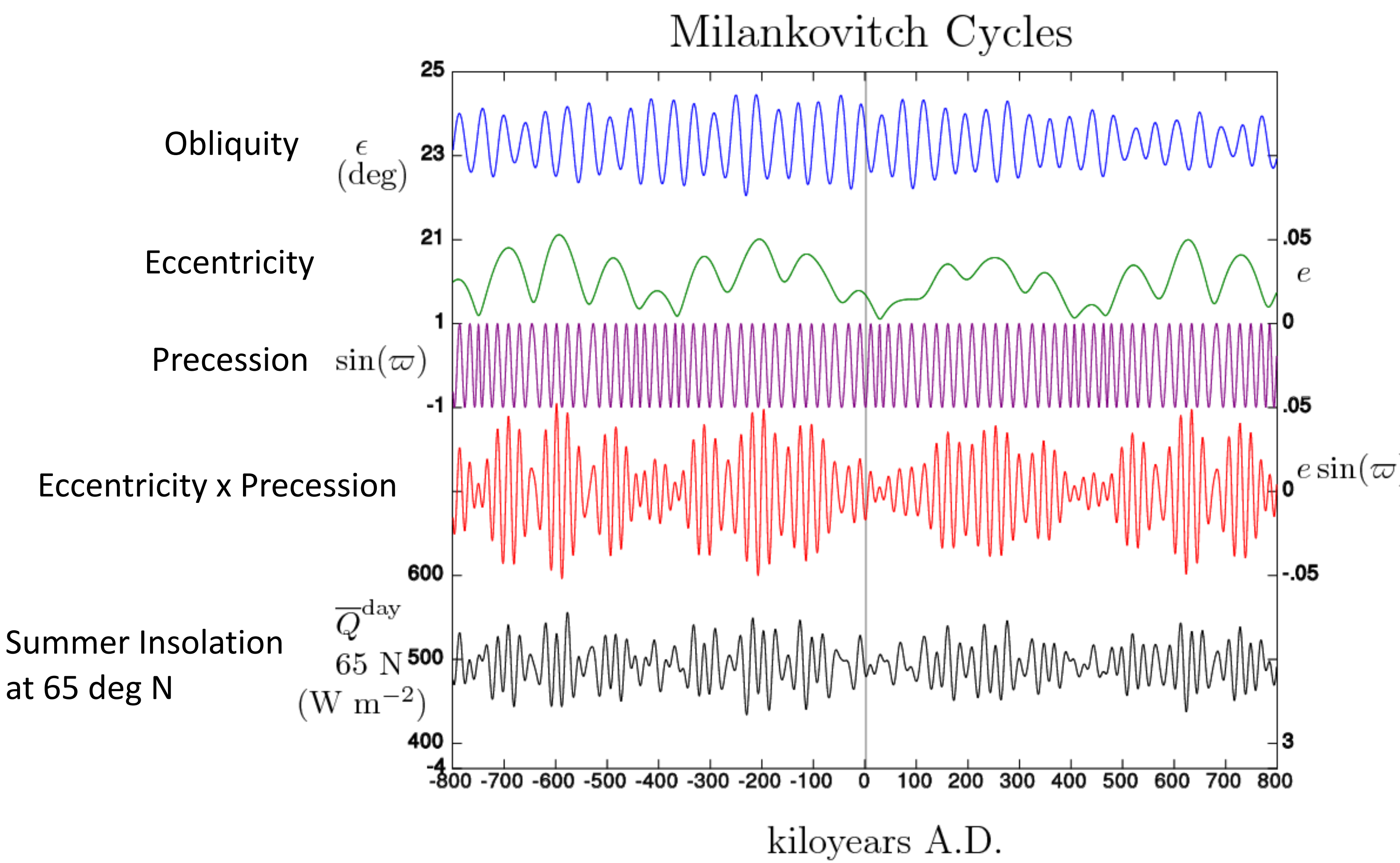
- Eccentricity
  - 100,000 yr cycles
  - range: 0.0034-0.058
  - present val.: 0.017
- Obliquity
  - 41,000 yr cycles
  - range: 22.1-24.5 deg
  - present val.: 23.4 deg
- Precession
  - 26,000 yr cycles

Milutin Milanković 1879-1958
Serbian astronomer

Predicting Solar Insolation on Summer Solstice at 65d N



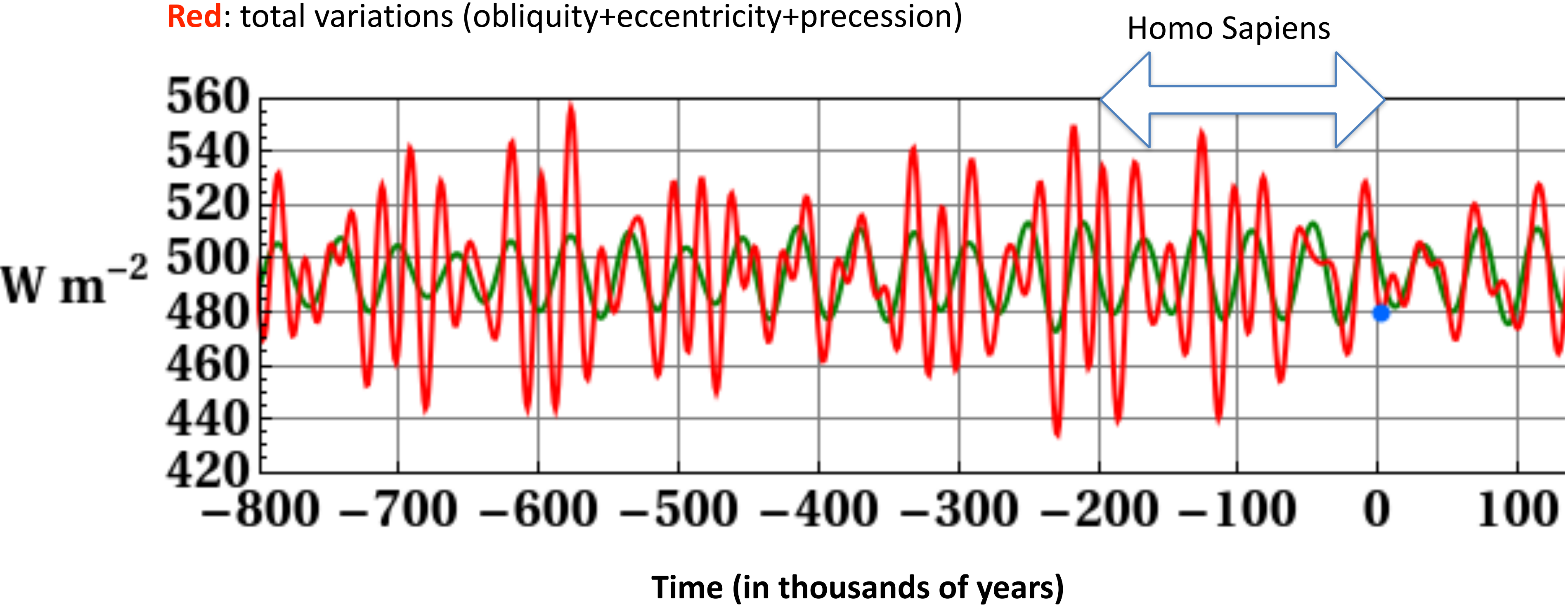
Predicted Solar Insolation



Milankovitch calculated that Ice Ages occur either every 41 kyrs or 100 kyrs, following the obliquity cycle or the eccentricity cycle

Green: obliquity-caused variations

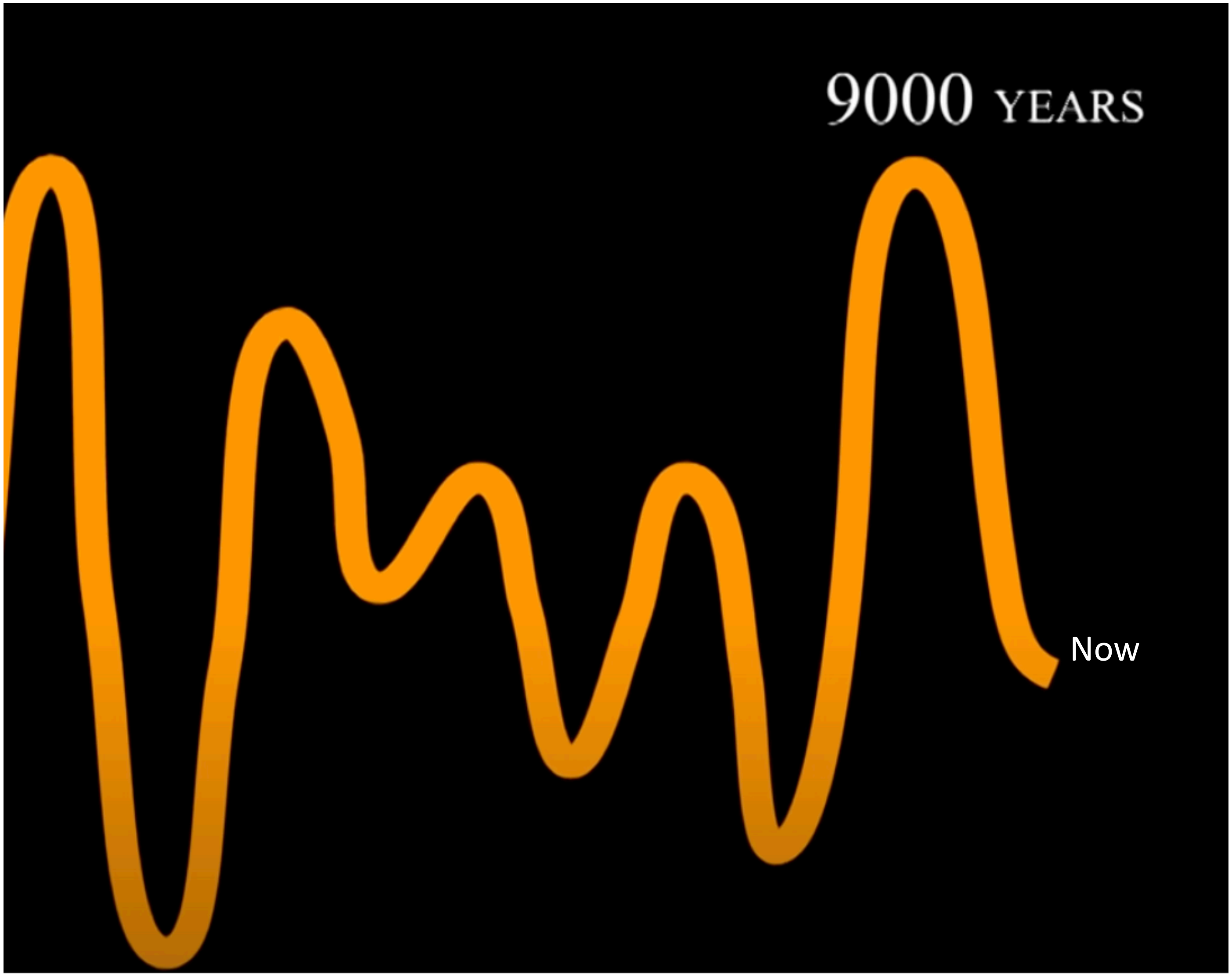
Red: total variations (obliquity+eccentricity+precession)



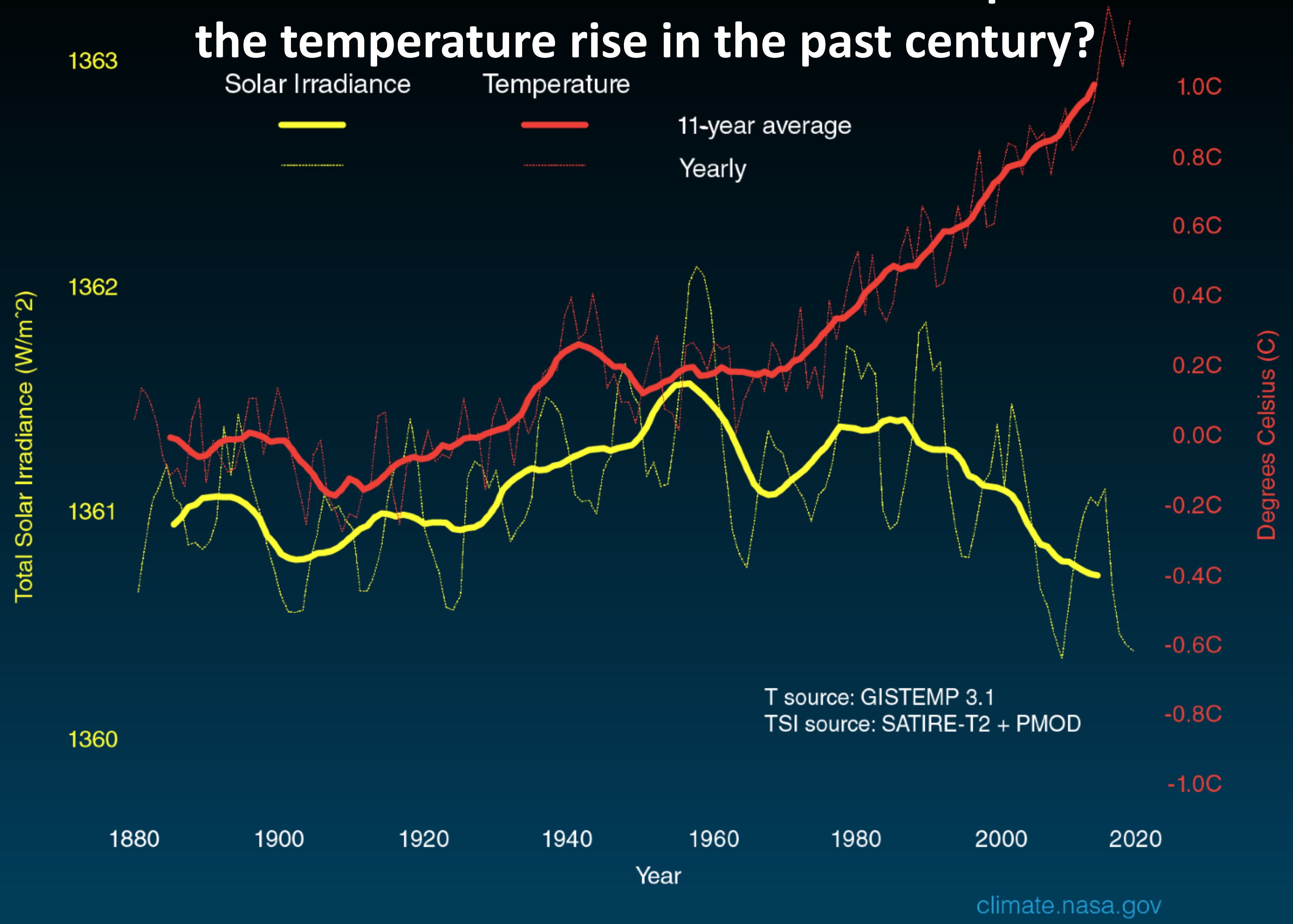
Average solar irradiance (insolation) at latitude of 65 deg N on summer solstice over the past million years

Where are we now in the Cycle?

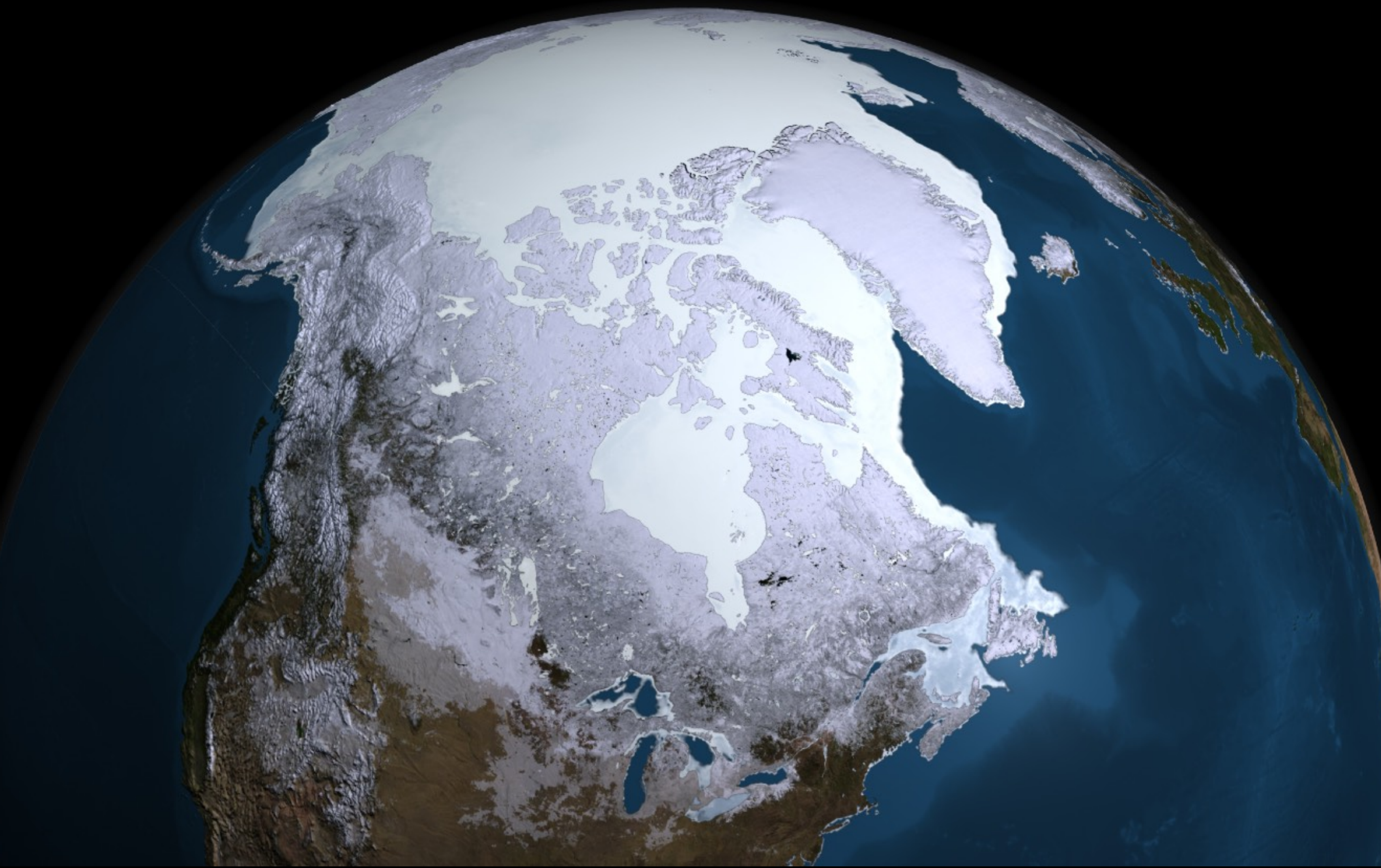
Obliquity: Intermediate and decreasing, Northern Summer at Aphelion
-> Lower Insolation in N hemisphere -> Less snow melt in N. summer -> Colder climate



How does the solar insolation curve compare with the temperature rise in the past century?

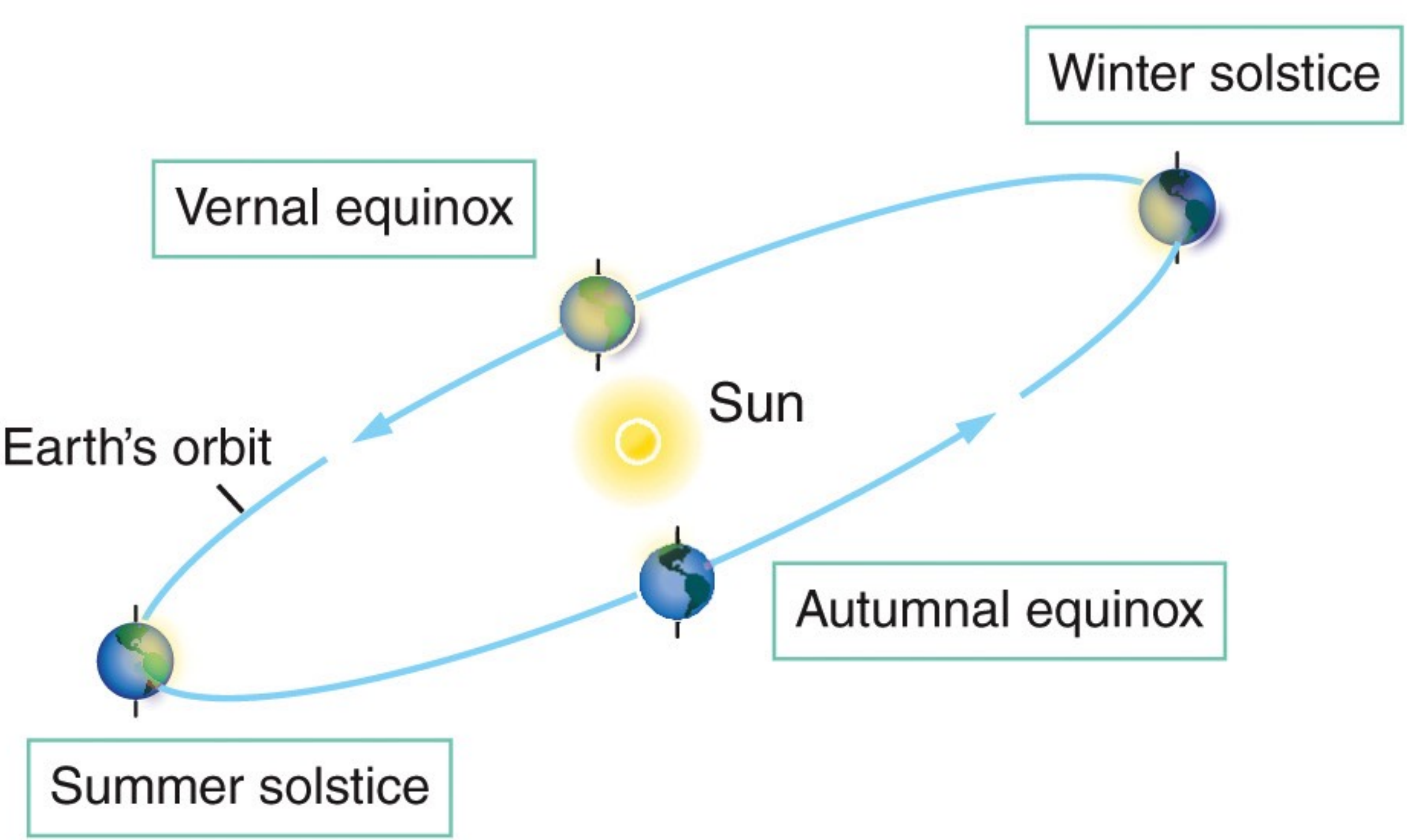


Longterm Climate Change & Earth's Fine Motions

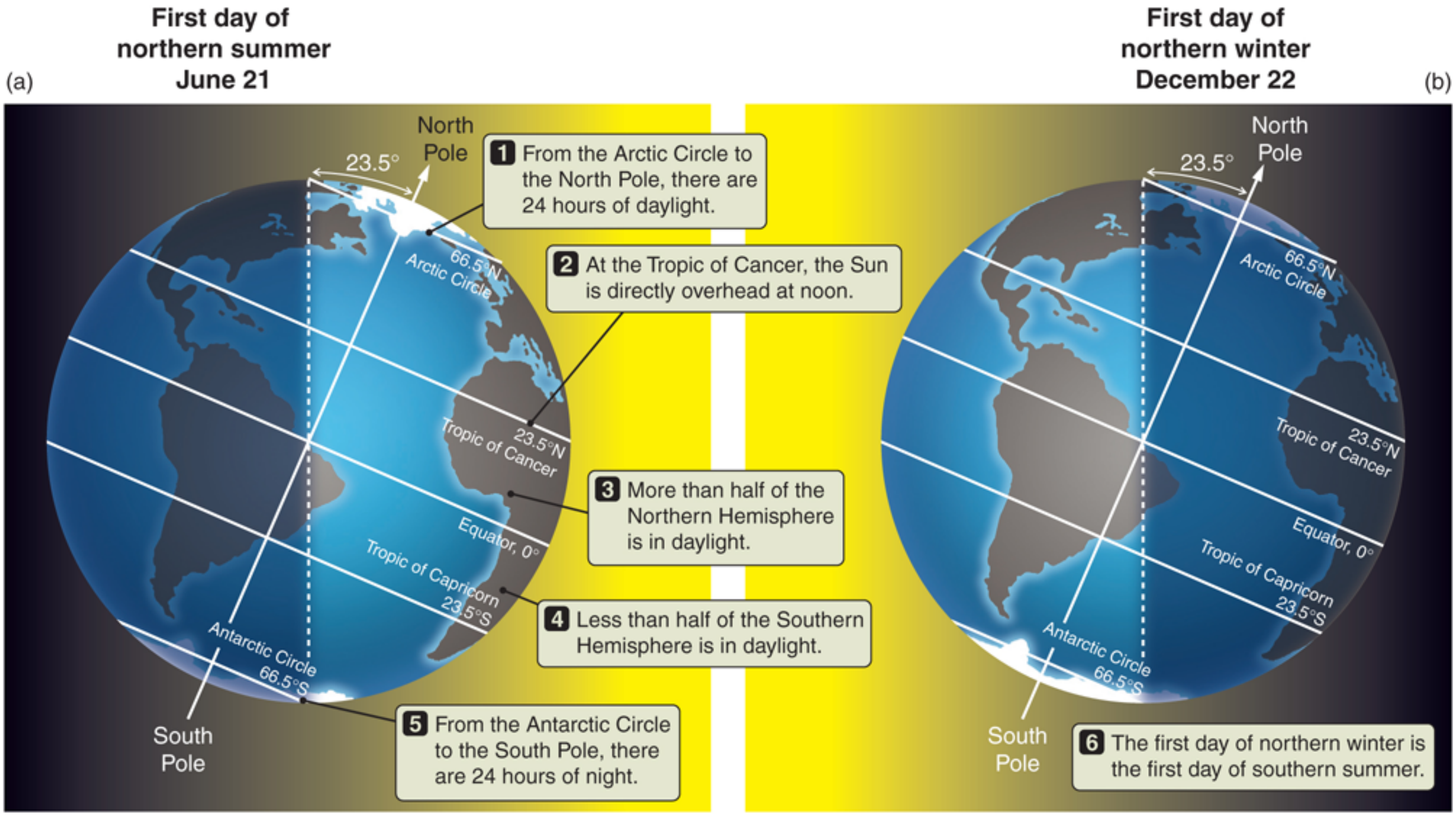


Short-term Cycles of Earth's Motions

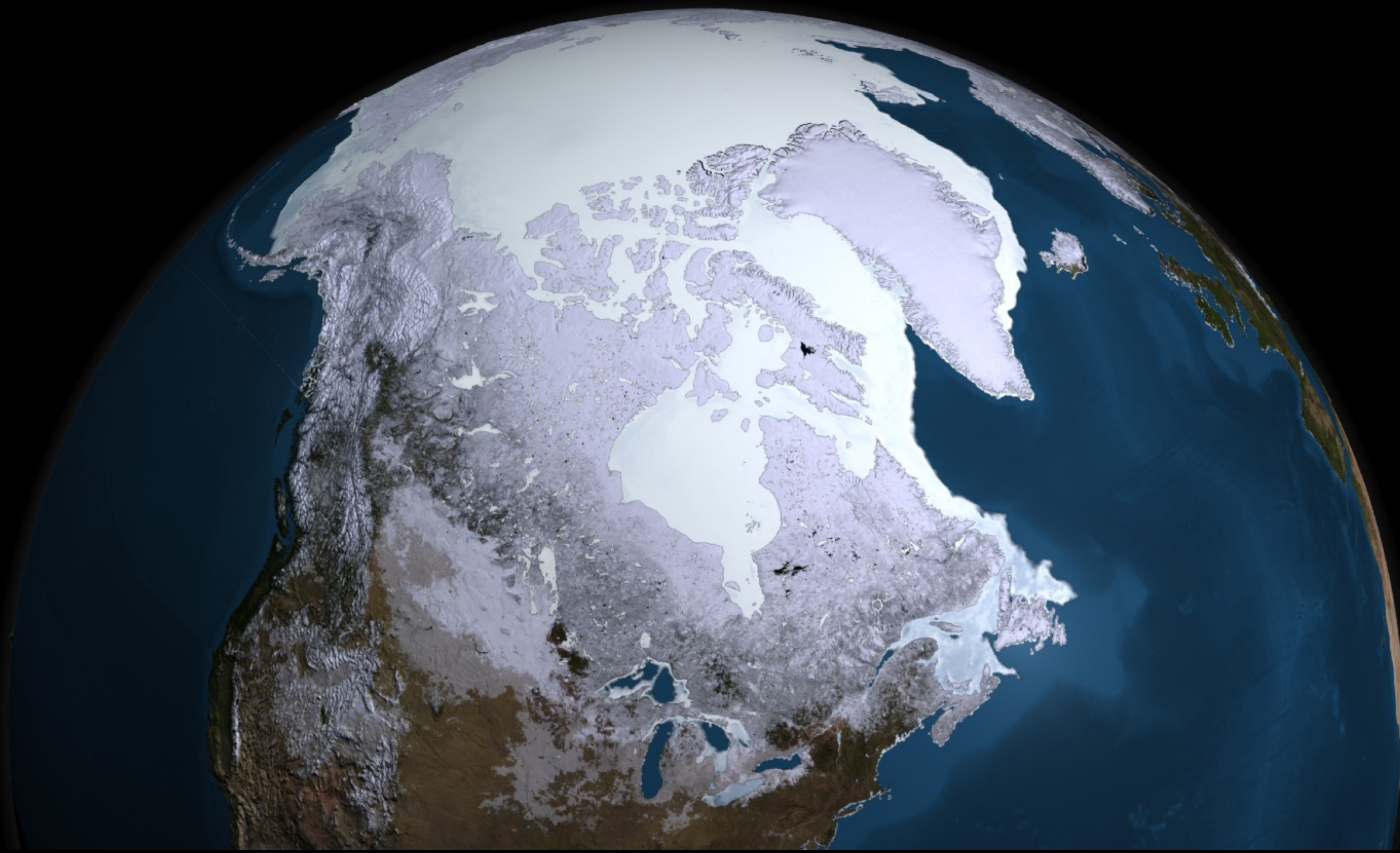
daily rotation & yearly revolution



- Obliquity and Seasons



The Last Ice Age: 115-12 kyrs ago
Maximum Ice Coverage: 26-20 kyrs ago
Ice covered all of Canada, down to Missouri

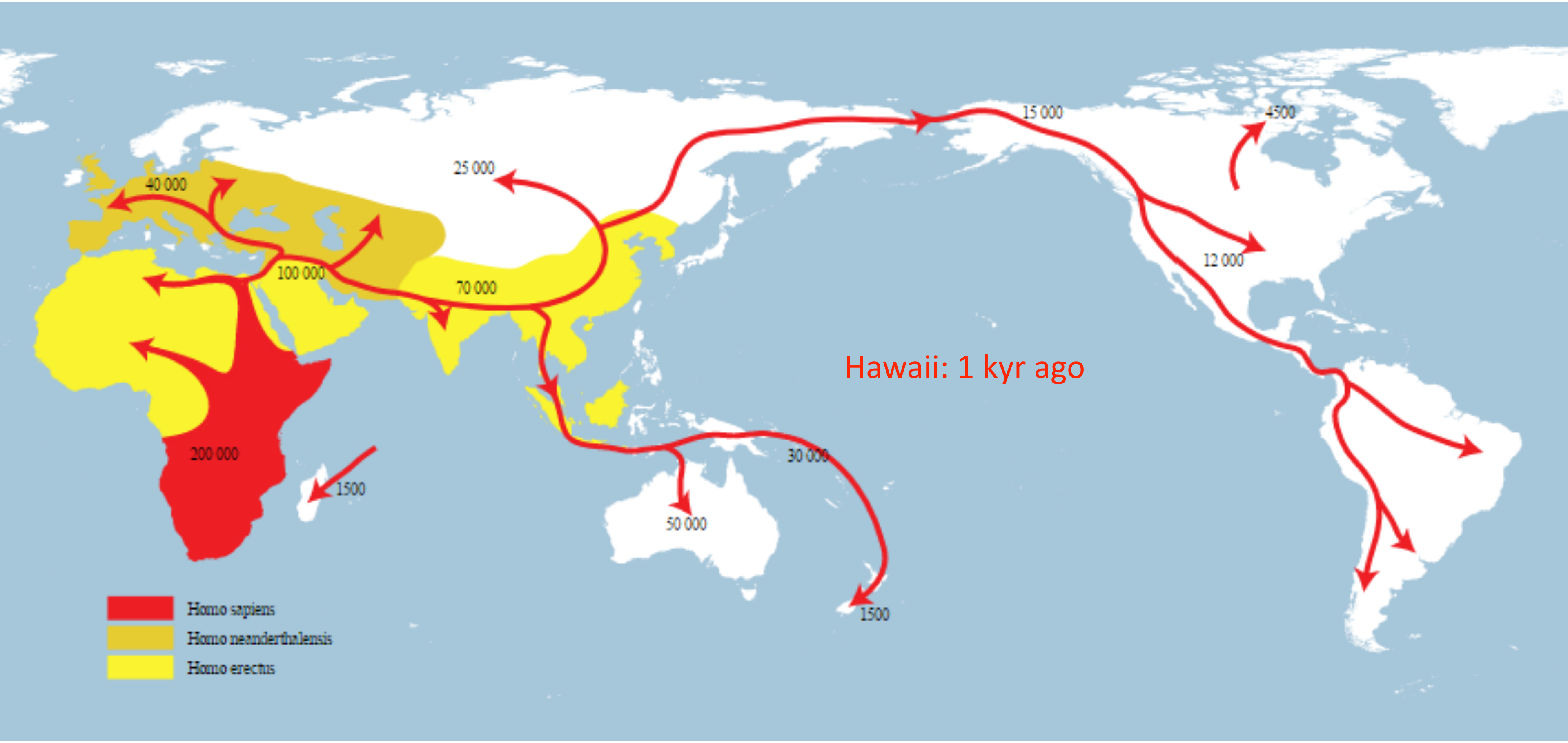


The Spread of *Homo Sapiens* across the Continents

The Last Glacial Period: 115 - 12 kyrs ago

Europe & Asia: 70 - 40 kyrs ago

North America: 12 kyrs ago



Hawaii: 1 kyr ago

Australia: 50 kyrs ago

Long-term Cycles of Earth's Motions

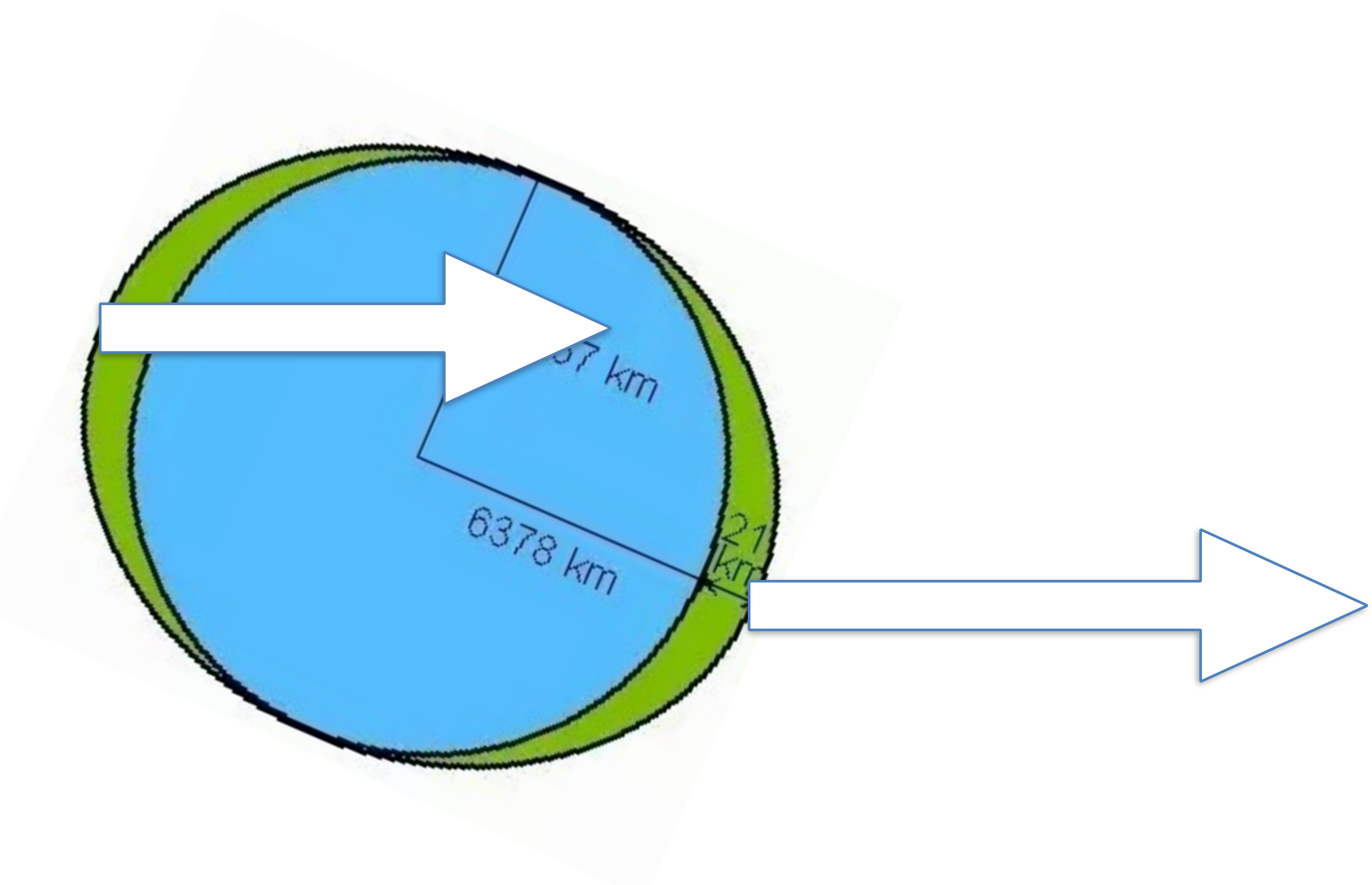
eccentricity, obliquity, precession

Axial Precession (Wobble)

26,000-year cycles

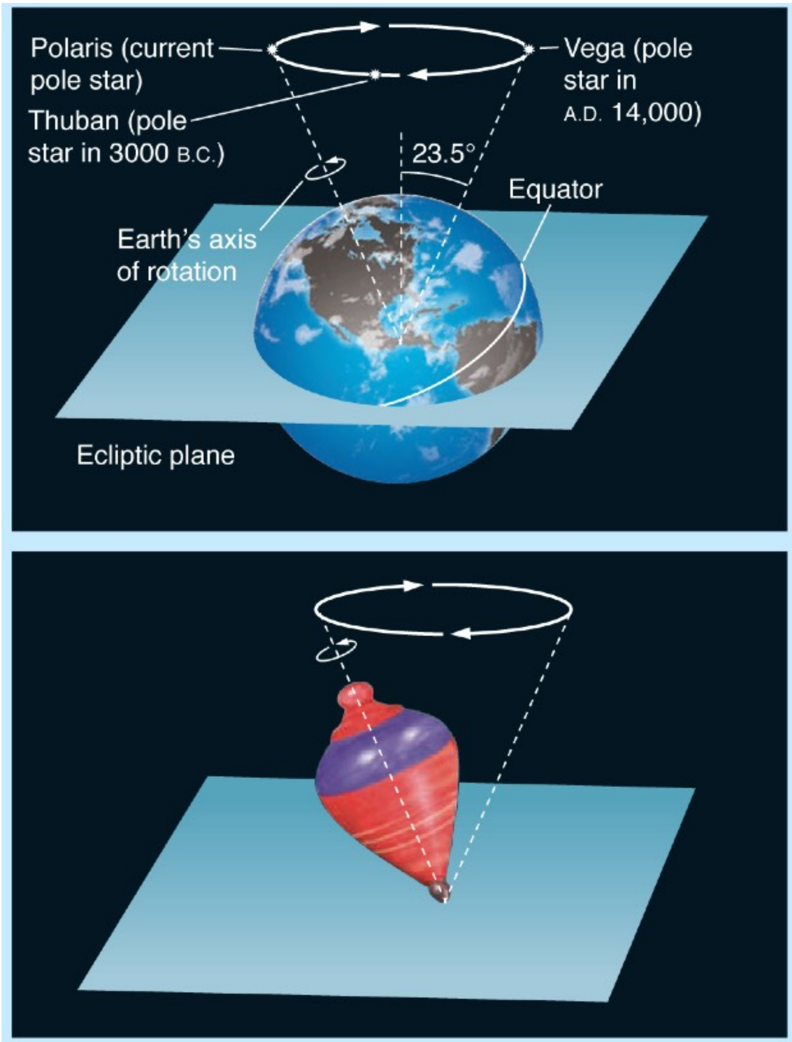
climate.nasa.gov

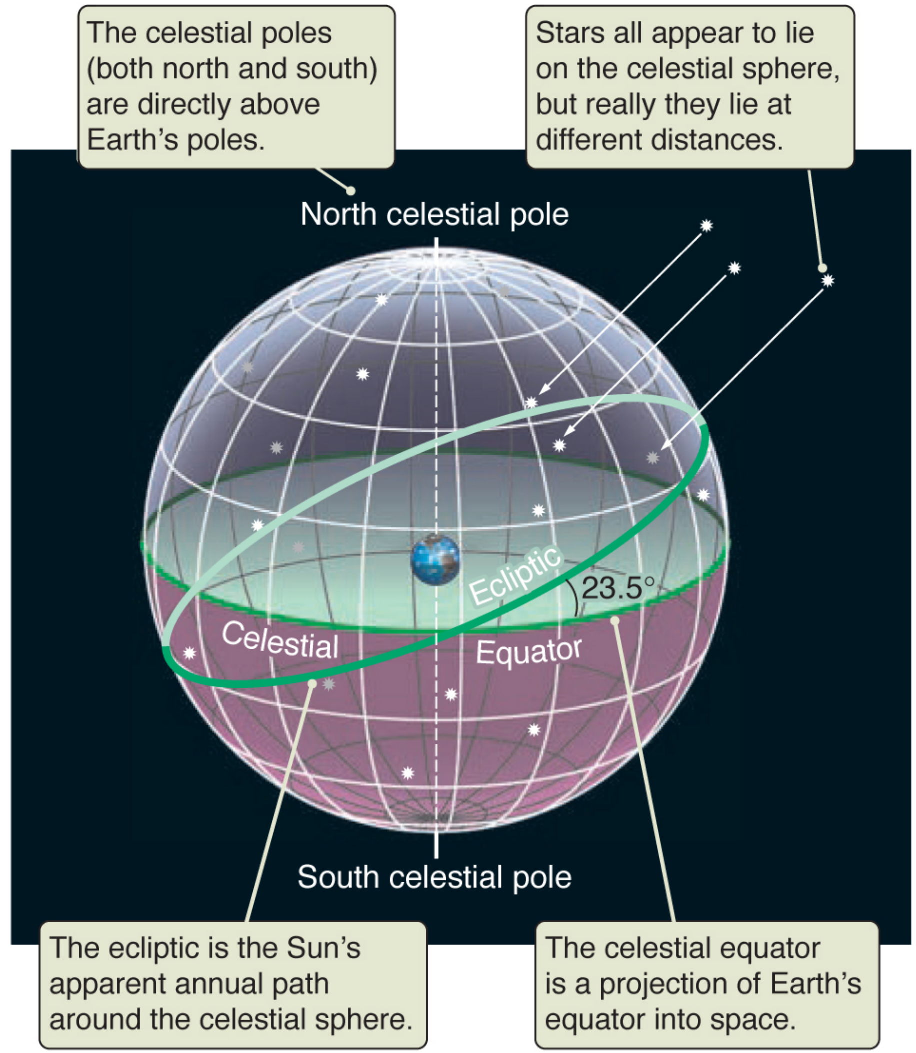
Tidal forces on Earth’s Equatorial Bulge caused most of the precession



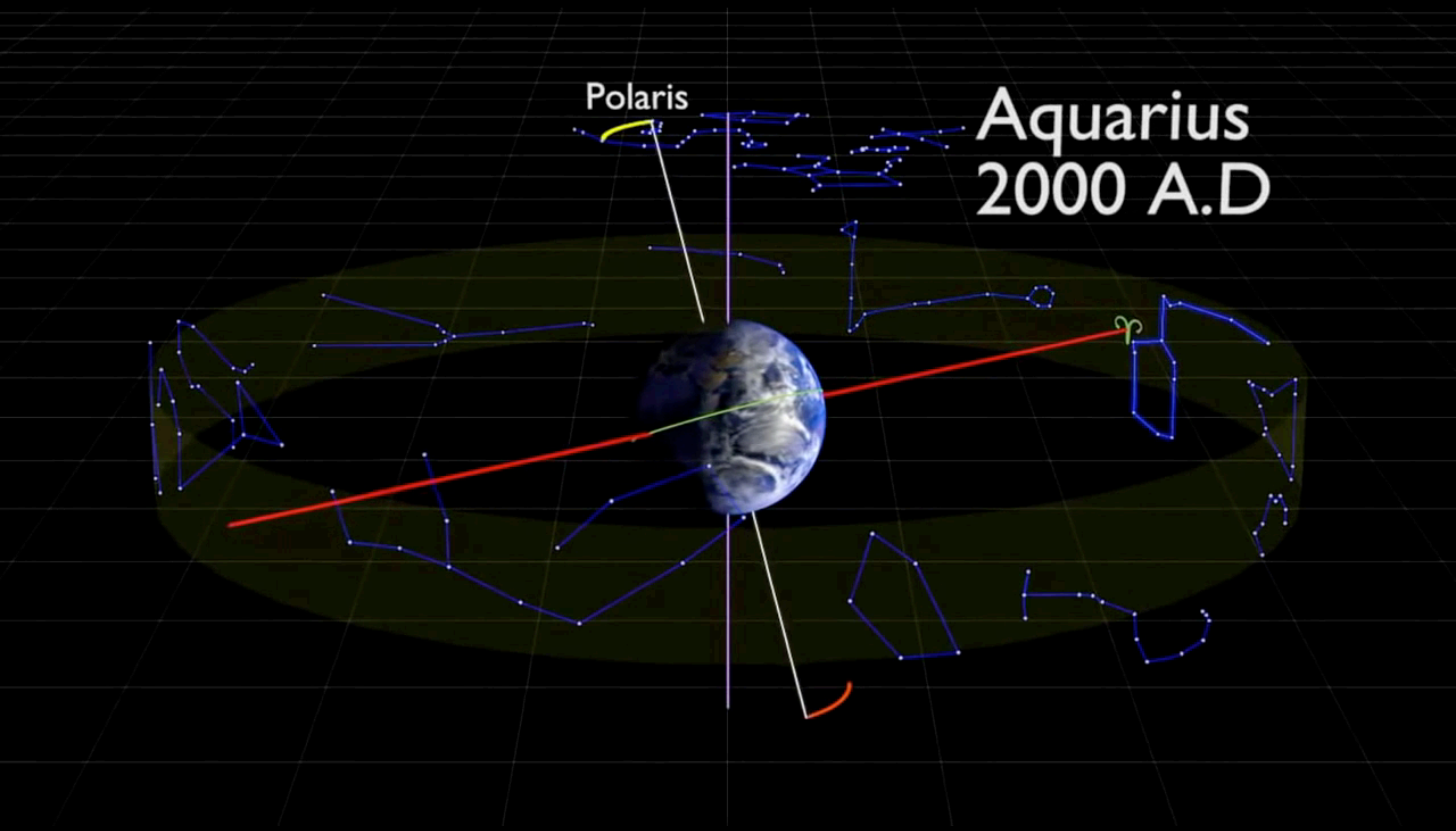
Moon & Sun

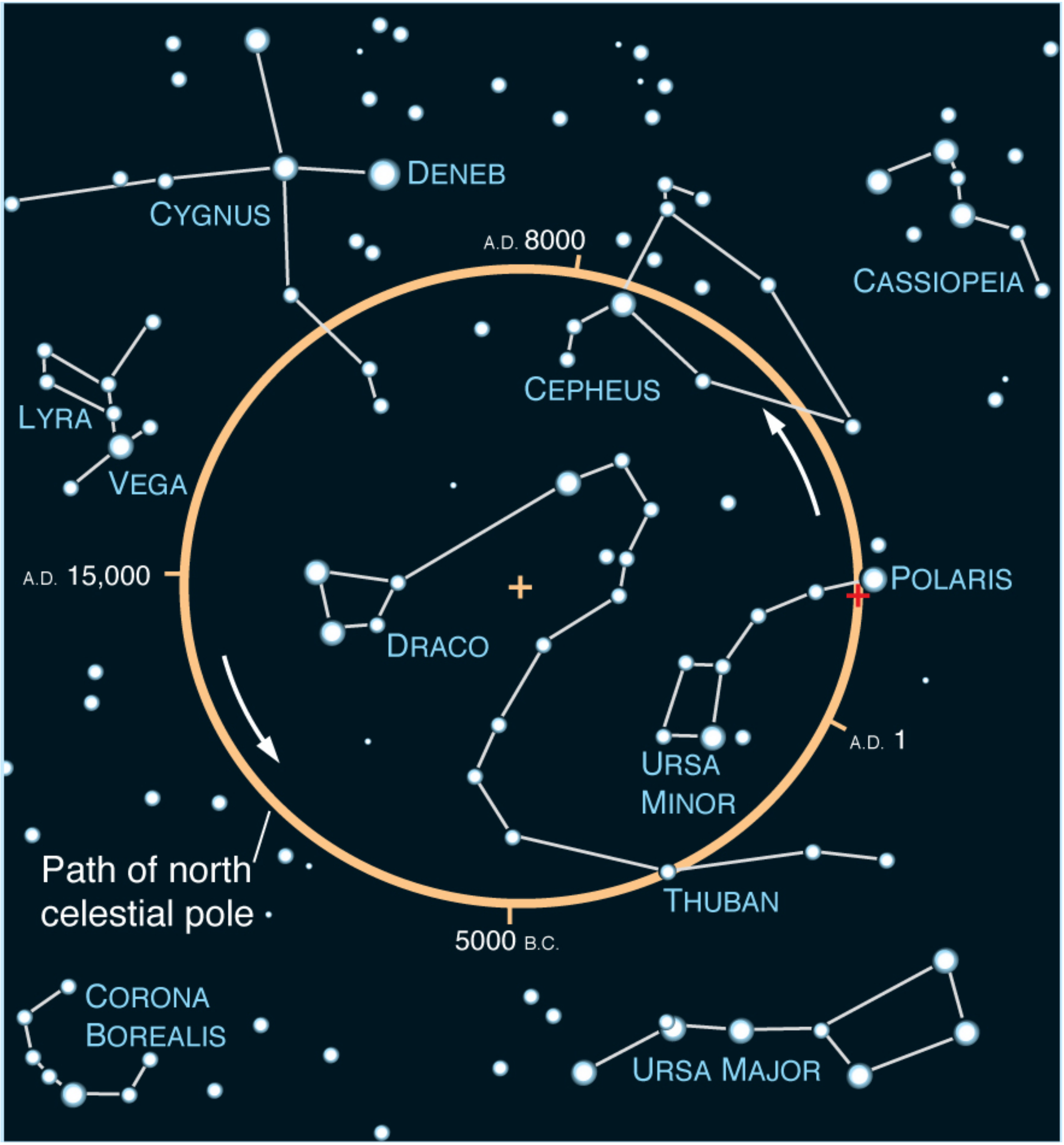
Earth's precession changes the celestial coordinates of distant objects





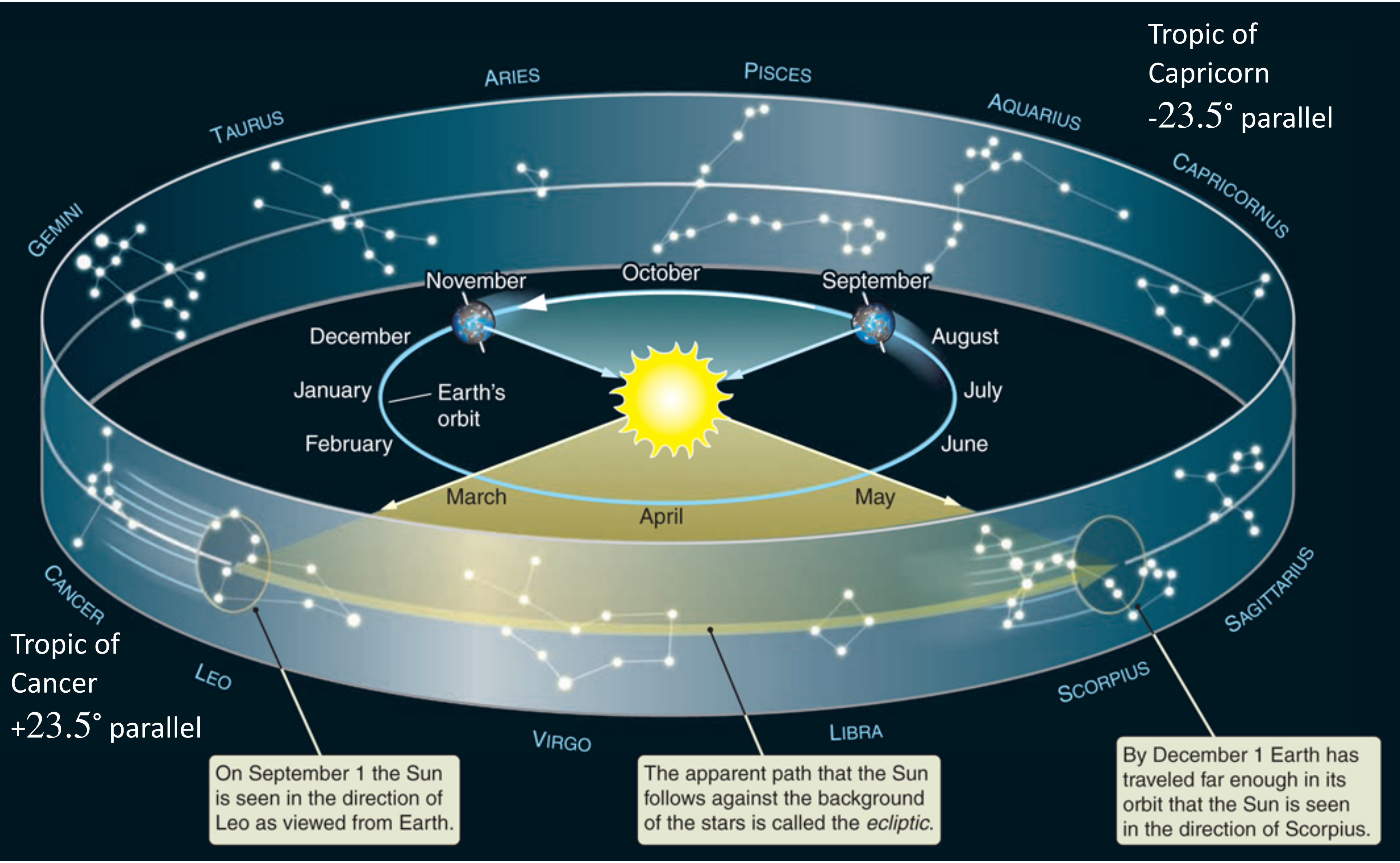
Precession: The Drift of Vernal Equinox & the NCP





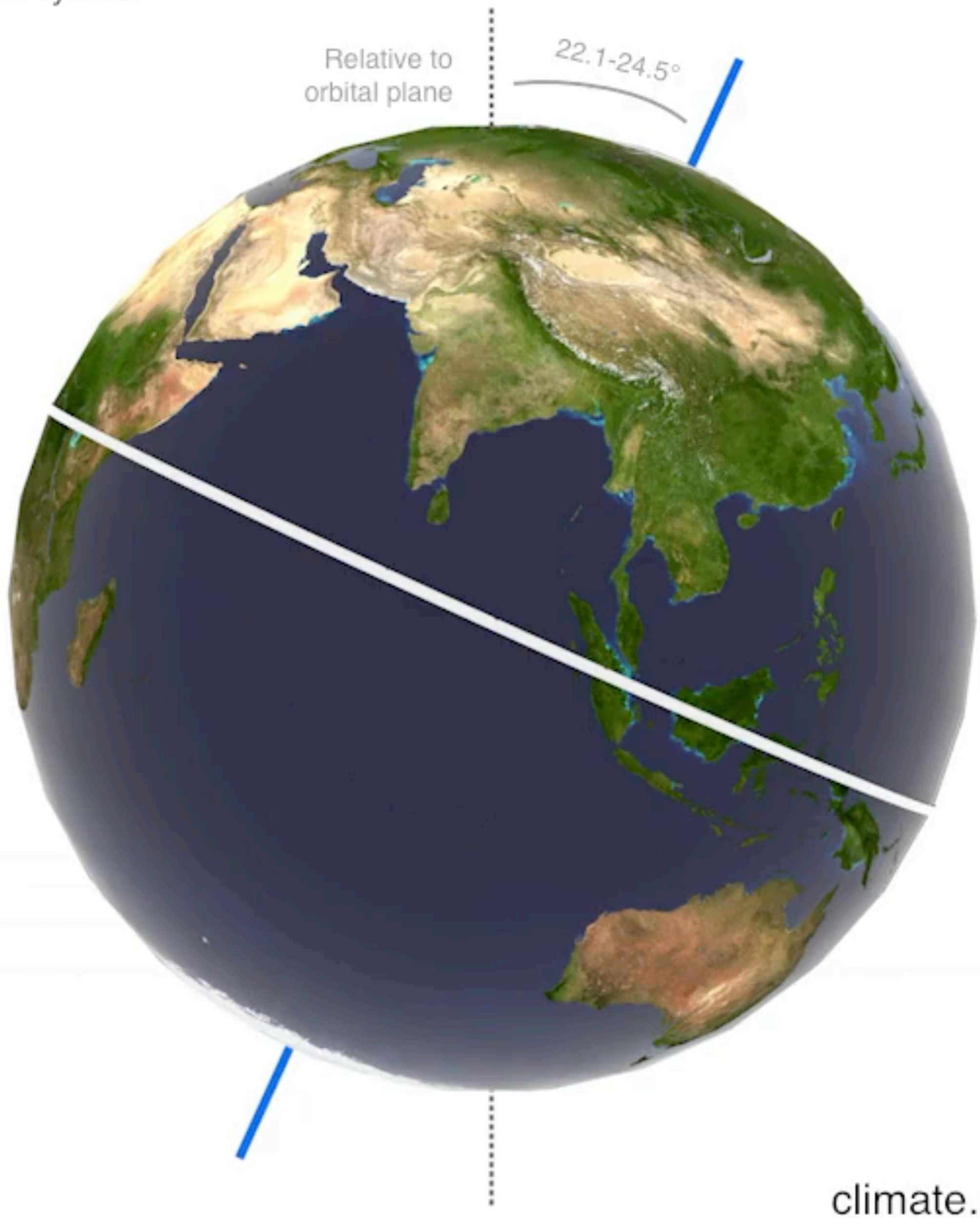
- Currently the north celestial pole is near the bright star Polaris.
- In 10000 years, it will be close to Vega.

- Because of the Earth's precession, the location of the Vernal Equinox moves along the ecliptic, changing the celestial coordinates (R.A. & Dec) and messing up the zodiac of each month.
- Tropic of Cancer has now become Tropic of Taurus (the Sun's constellation on Summer Solstice),
- Tropic of Capricorn has now become Tropic of Sagittarius (the Sun's constellation on Winter Solstice)



Changes in Obliquity (Tilt)

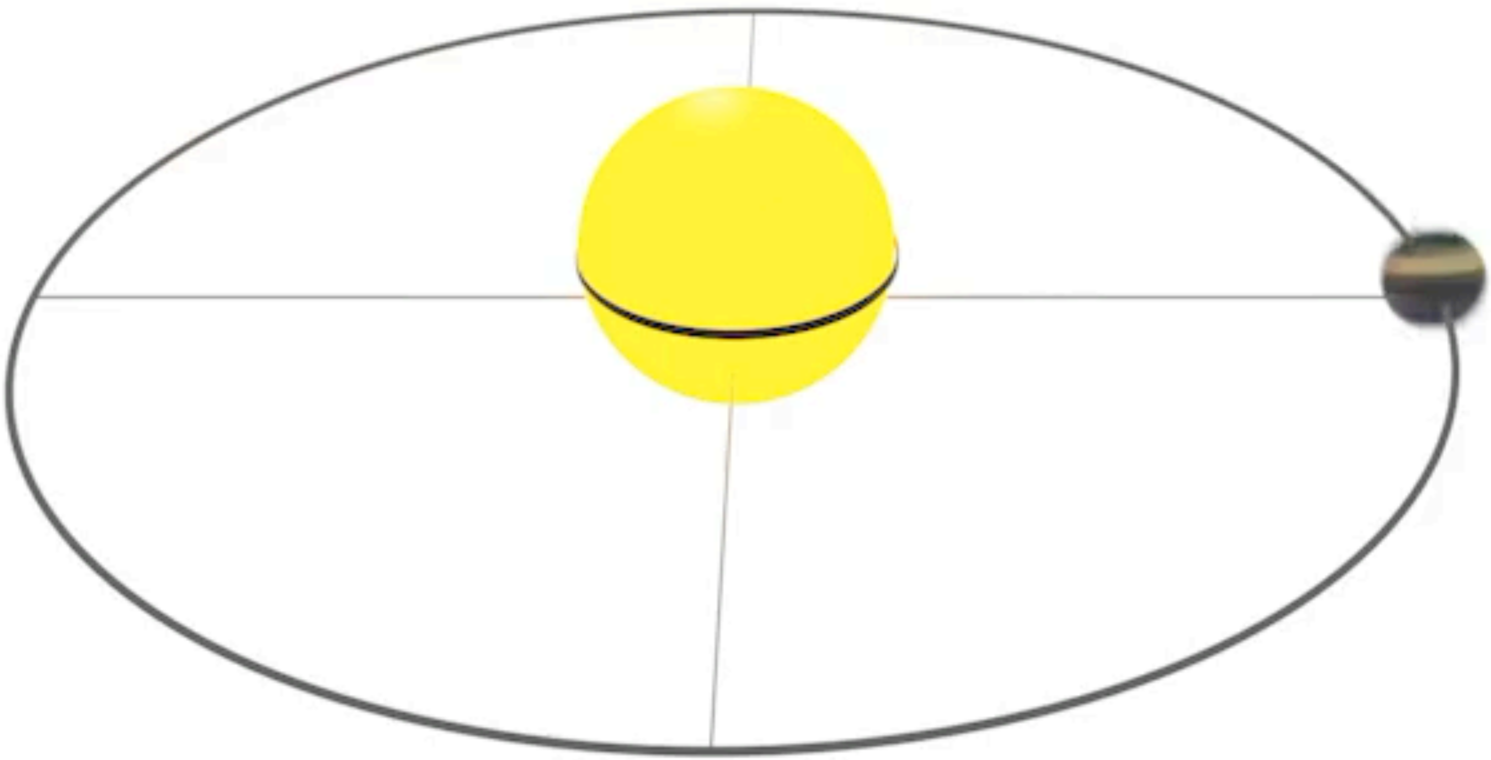
41,000-year cycles



climate.nasa.gov

Changes in Eccentricity (Orbit Shape)

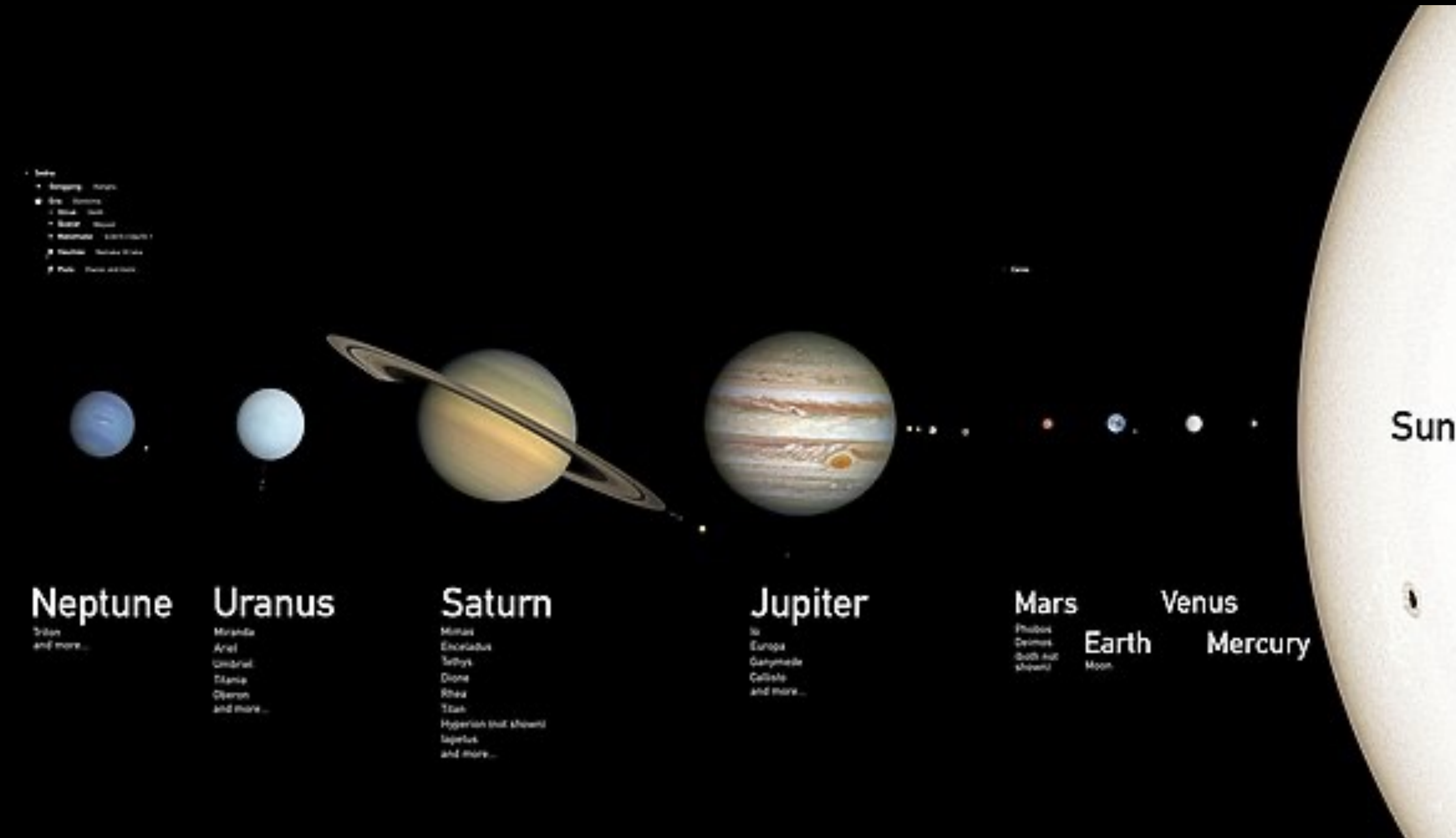
100,000-year cycles



*Changes in eccentricity exaggerated so the effect can be seen. Earth's orbit shape varies between 0.0034 (almost a perfect circle) to 0.058 (slightly elliptical).

climate.nasa.gov

Gravitational perturbations from other planets

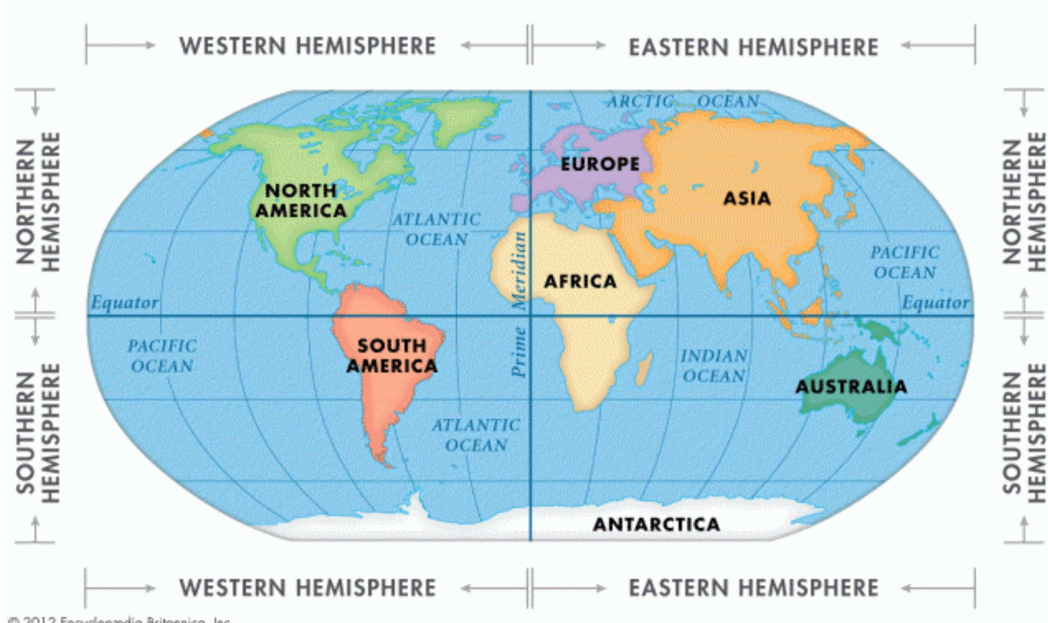


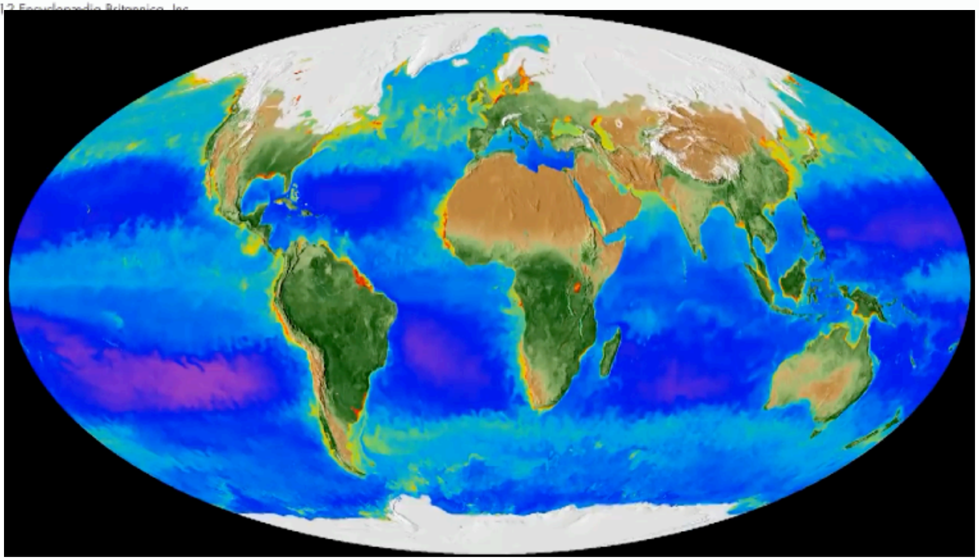
Milankovitch Cycles & Ice Ages

eccentricity, obliquity, precession

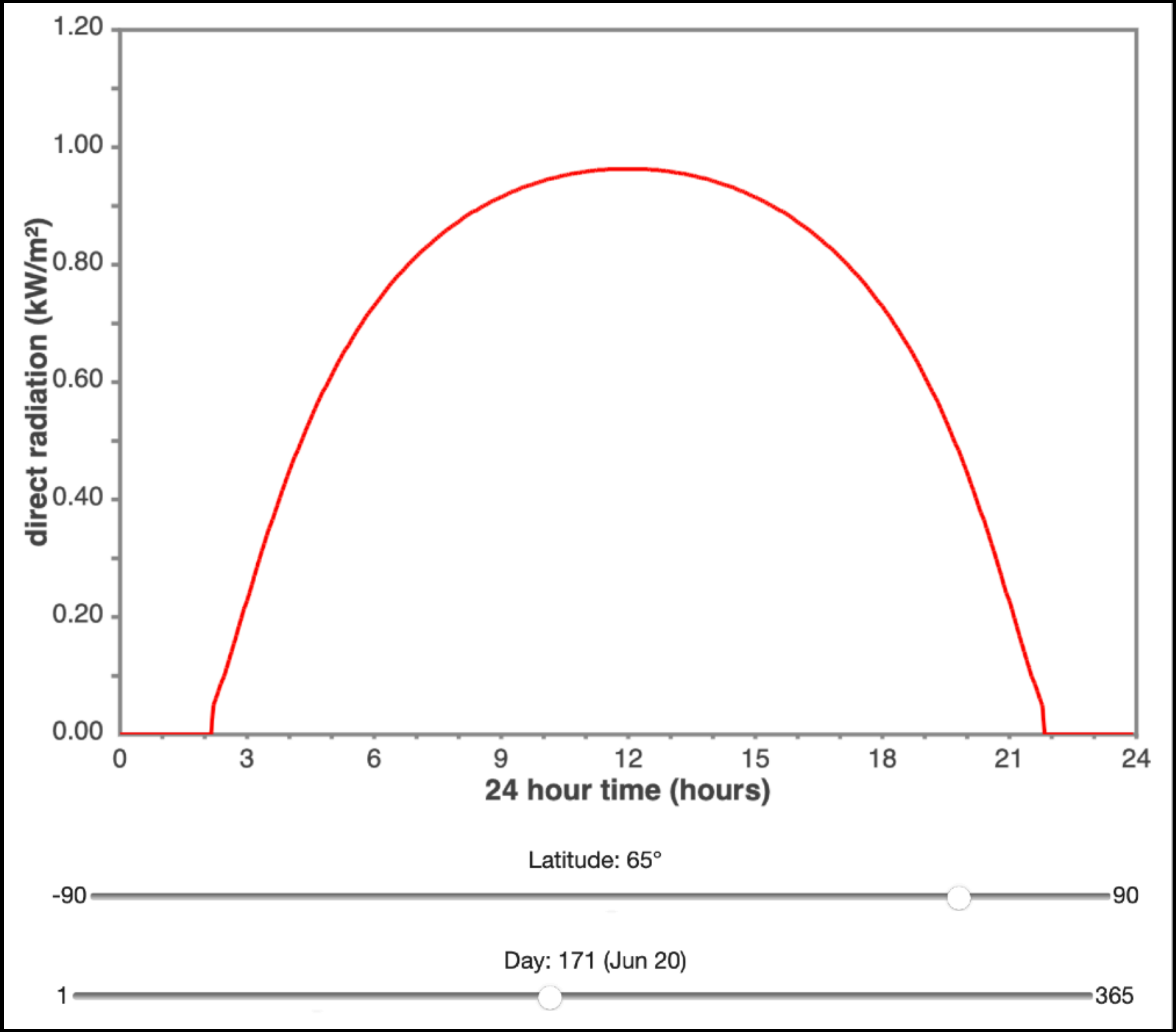
How to make an ice age?

- **The key is to reduce the amount of ice melting in the northern summer**
- Northern Hemisphere: 40% land, 60% ocean
- Southern Hemisphere: 20% land, 80% ocean
- **milder summer** in northern hemisphere -> **less ice melt** during the summer -> **more reflection** of sunlight -> **colder average temperature**





Solar Insolation on Summer Solstice at 65d N

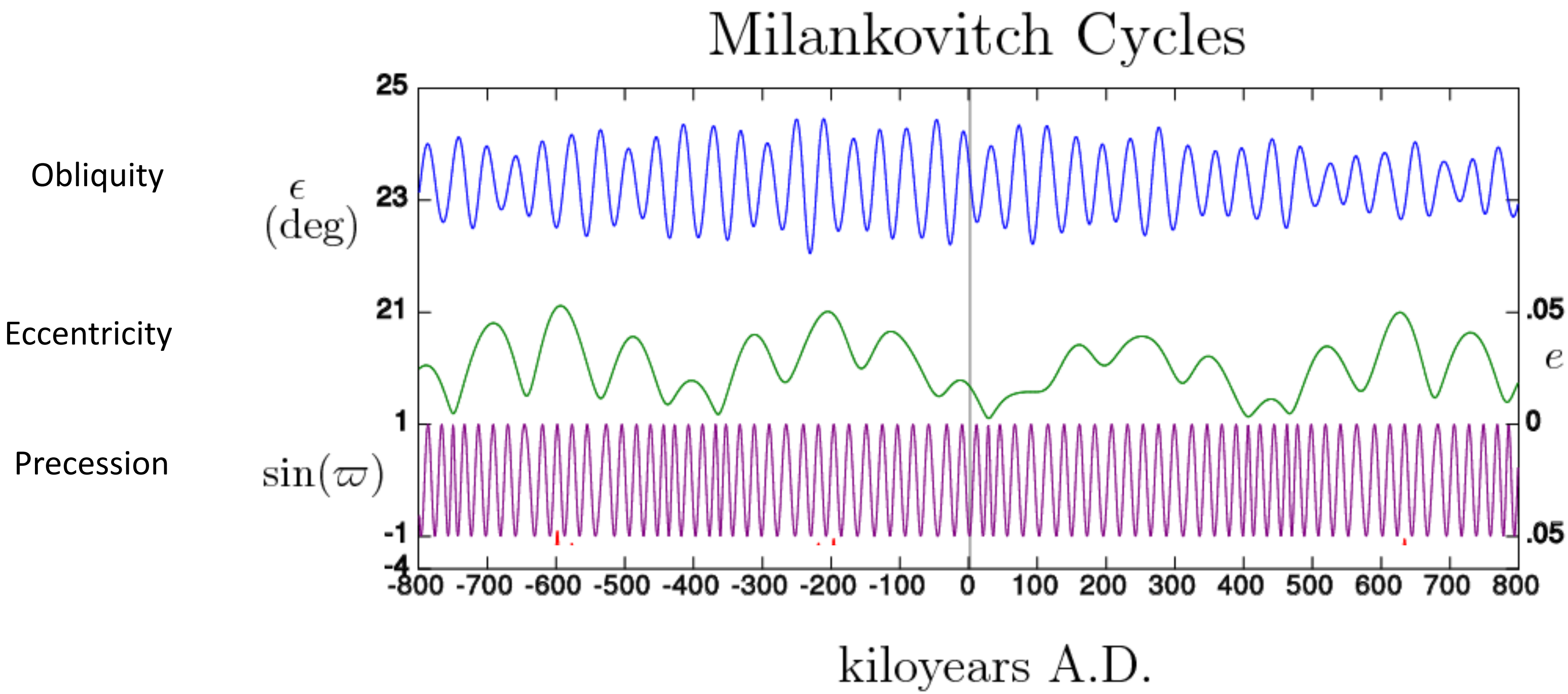


https://www.pveducation.org/pvcdrom/properties-of-sunlight/calculation-of-solar-insolation

Milankovitch use changes in Earth's motion to explain its long-term climate changes

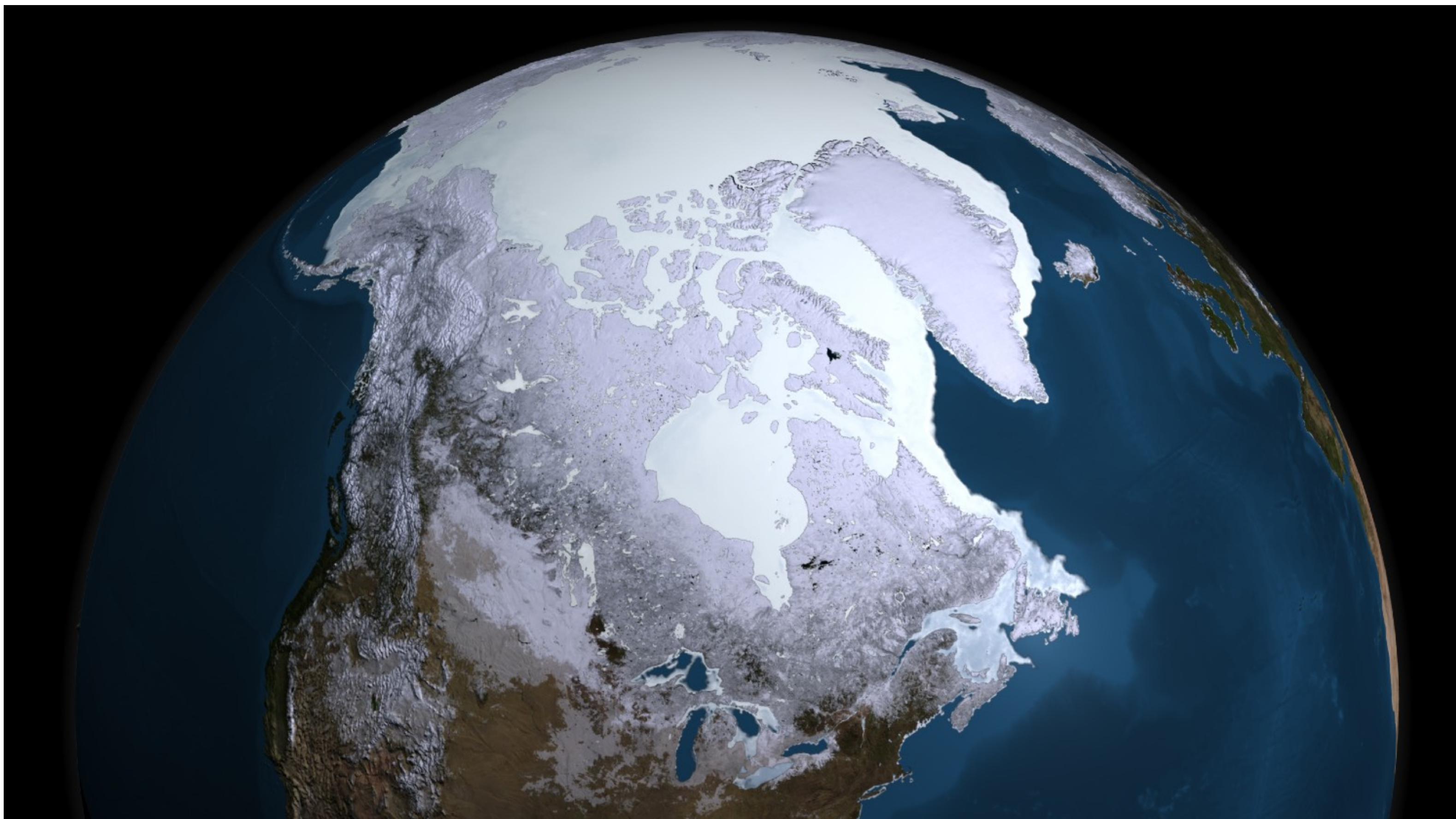
- Eccentricity
  - 100,000 yr cycles
  - range: 0.0034-0.058
  - present val.: 0.017
- Obliquity
  - 41,000 yr cycles
  - range: 22.1-24.5 deg
  - present val.: 23.4 deg
- Precession
  - 26,000 yr cycles

Milutin Milanković 1879-1958
Serbian astronomer

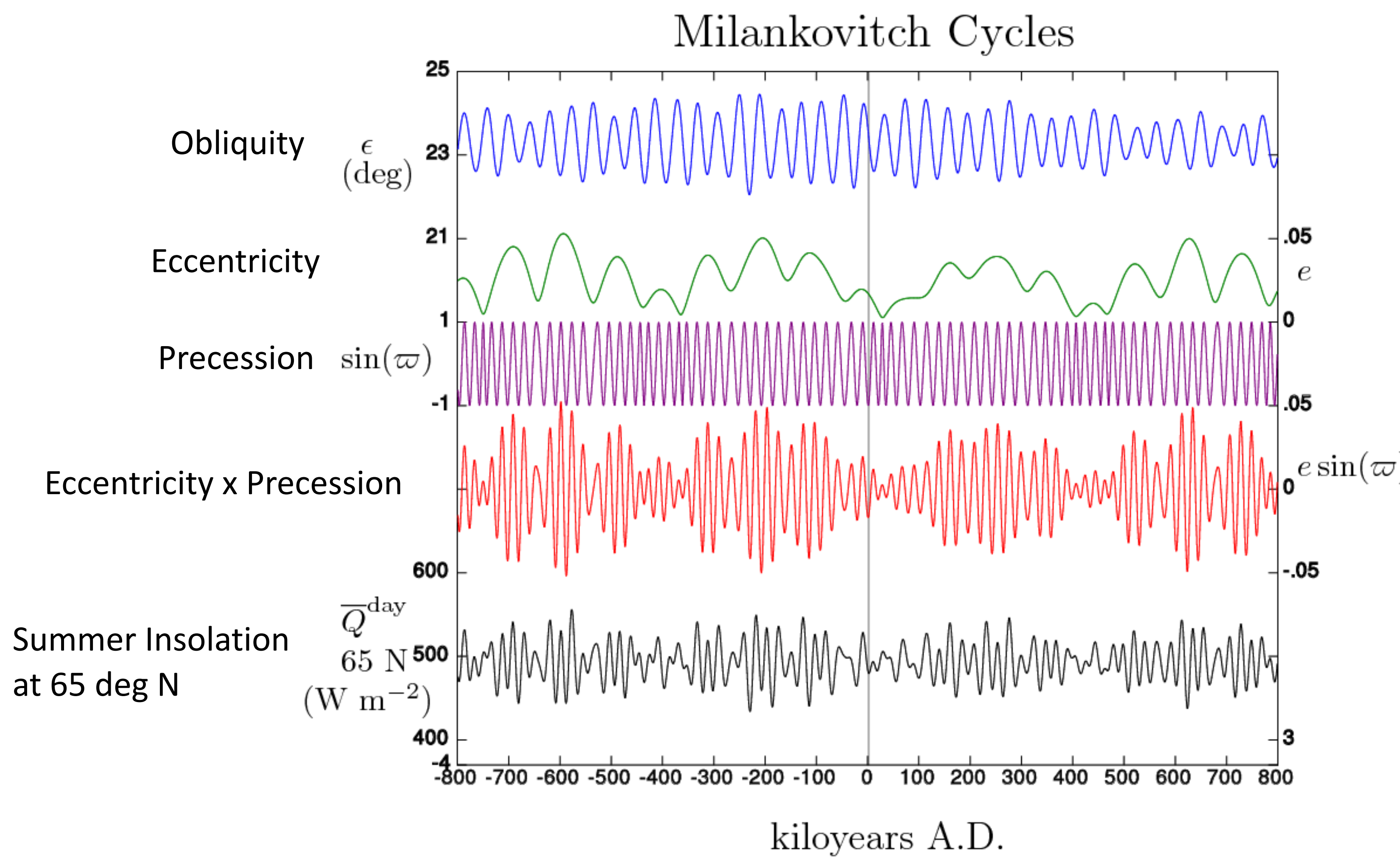

Milankovitch Cycles
Obliquity
ϵ (deg)
Eccentricity
Precession
$\sin(\varpi)$
e
25
23
21
1
-1
-4
.05
0
.05
-800 -700 -600 -500 -400 -300 -200 -100 0 100 200 300 400 500 600 700 800
kiloyears A.D.

Recipe to make an Ice Age

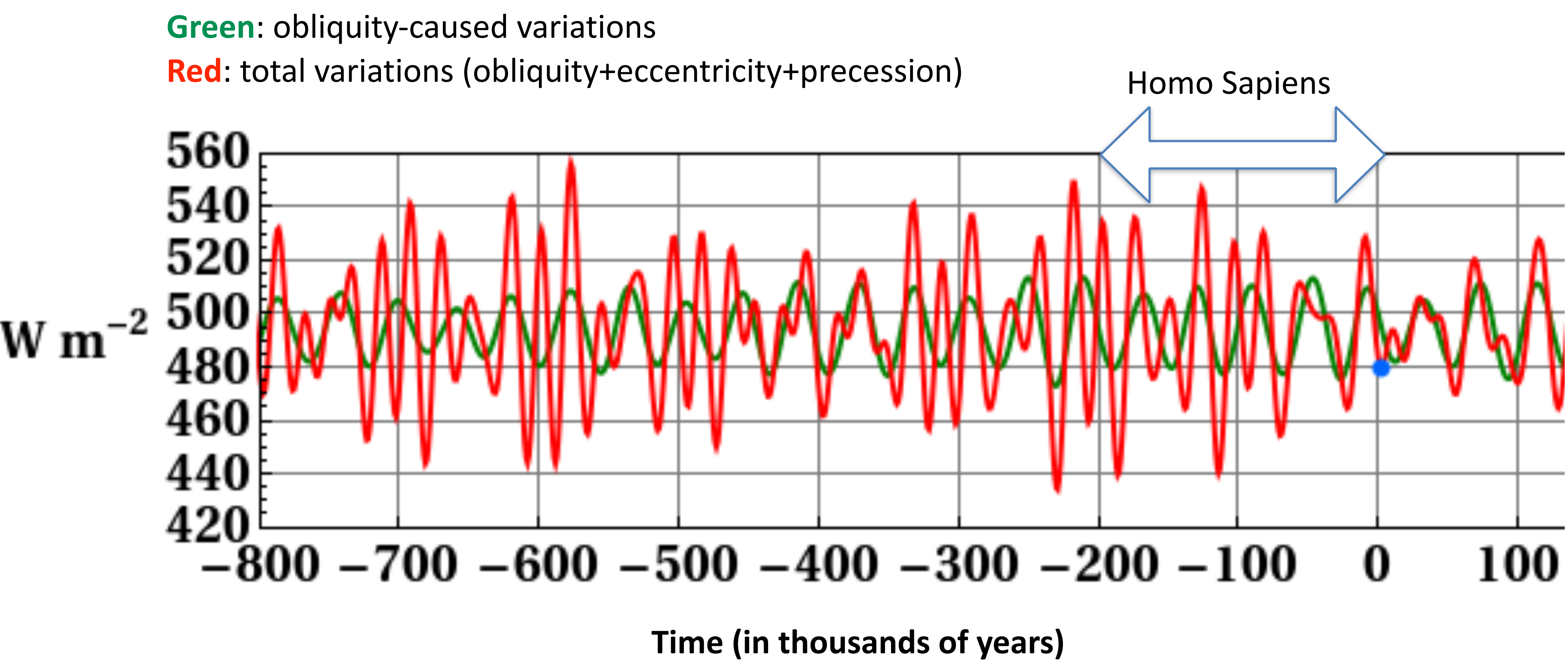
- High **eccentricity**, while **precession** shifts Northern Summer to **Aphelion**
- Low **obliquity**: less solar radiation in the summer at high northern latitudes
- These cause **milder summer** in northern hemisphere -> **less ice melt** during the summer -> **more reflection of sunlight** -> **colder** global temperature



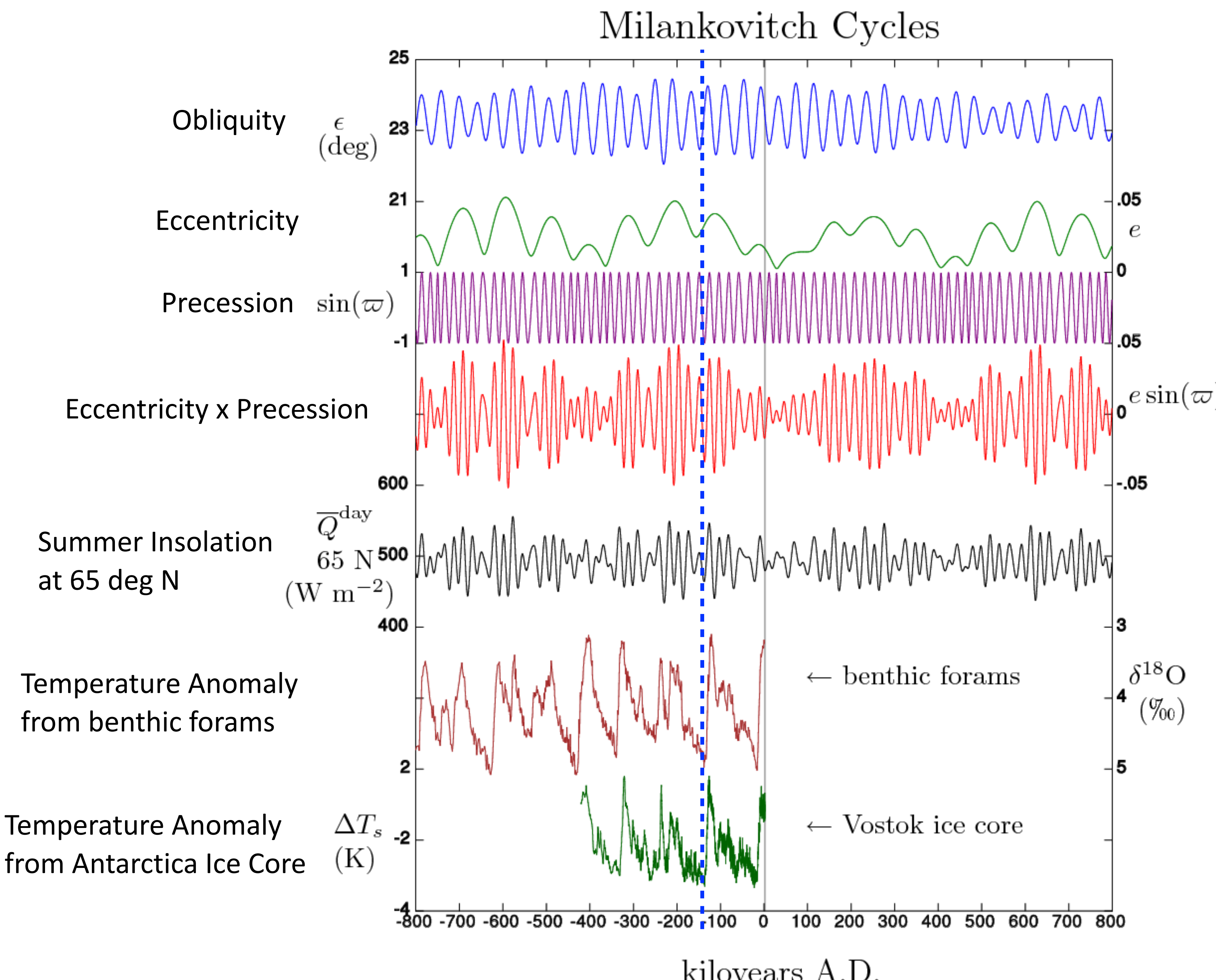
Predicted Solar Insolation



Milankovitch calculated that Ice Ages occur either every 41 kyrs or 100 kyrs, following the obliquity cycle or the eccentricity cycle



Average solar irradiance (insolation) at latitude of 65 deg N on summer solstice over the past million years



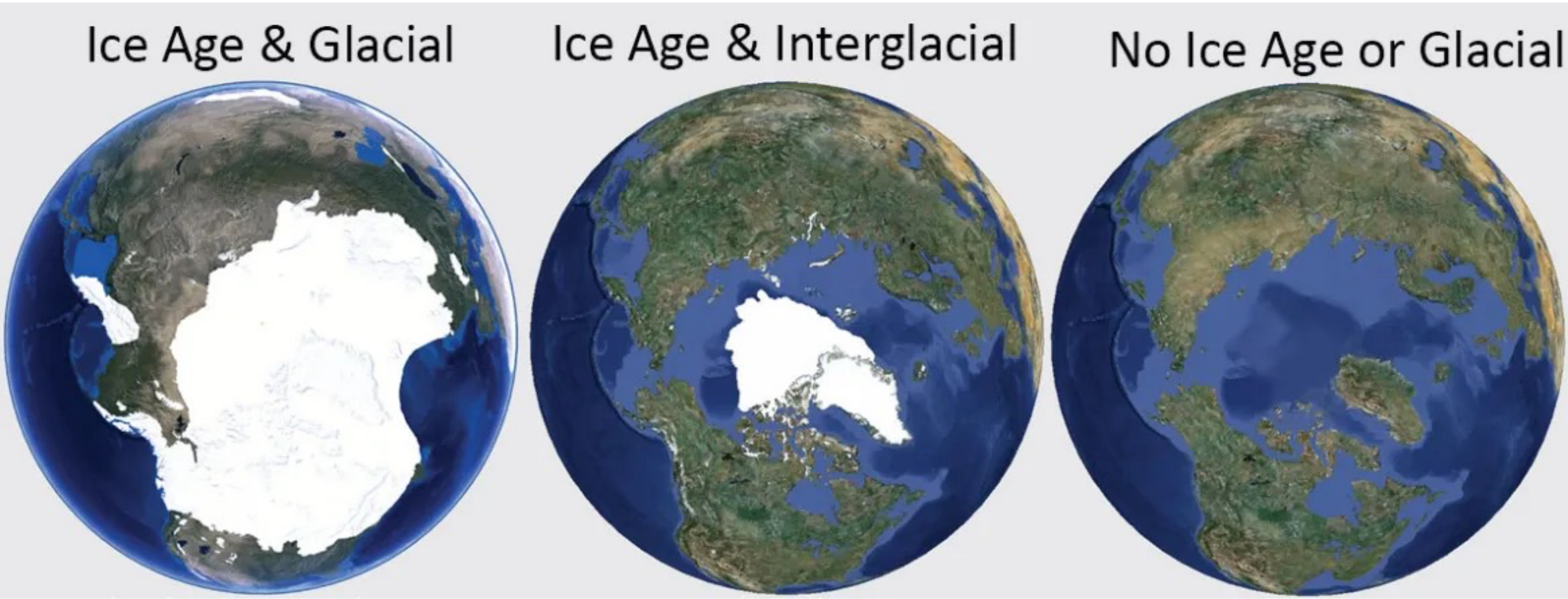
Milankovitch Cycles
Obliquity
ϵ (deg)
Eccentricity
e
Precession
$\sin(\varpi)$
Eccentricity x Precession
$e \sin(\varpi)$
Summer Insolation at 65 deg N
$\overline{Q}^{\mathrm{day}}$ 65 N (W m^{-2})
Temperature Anomaly from benthic forams
← benthic forams
δ^{18}O (‰)
Temperature Anomaly from Antarctica Ice Core
ΔT_s (K)
← Vostok ice core
25
23
21
1
-1
600
500
400
2
-2
-4
.05
0
.05
0
-.05
3
4
5
-800 -700 -600 -500 -400 -300 -200 -100 0 100 200 300 400 500 600 700 800
kiloyears A.D.

Where are we now in the Cycle?

Obliquity: Intermediate and decreasing, Northern Summer at Aphelion

-> Lower Insolation in N hemisphere -> Less snow melt in N summer -> Colder climate

Milankovitch calculated that Ice Ages occur either every 41 kyrs or 100 kyrs, following the obliquity cycle or the eccentricity cycle, and we are currently on a **cooling trend** that started 6000 years ago



50,000 years later **present** **9000 years ago**

Milankovitch Cycles & Recent Global Warning

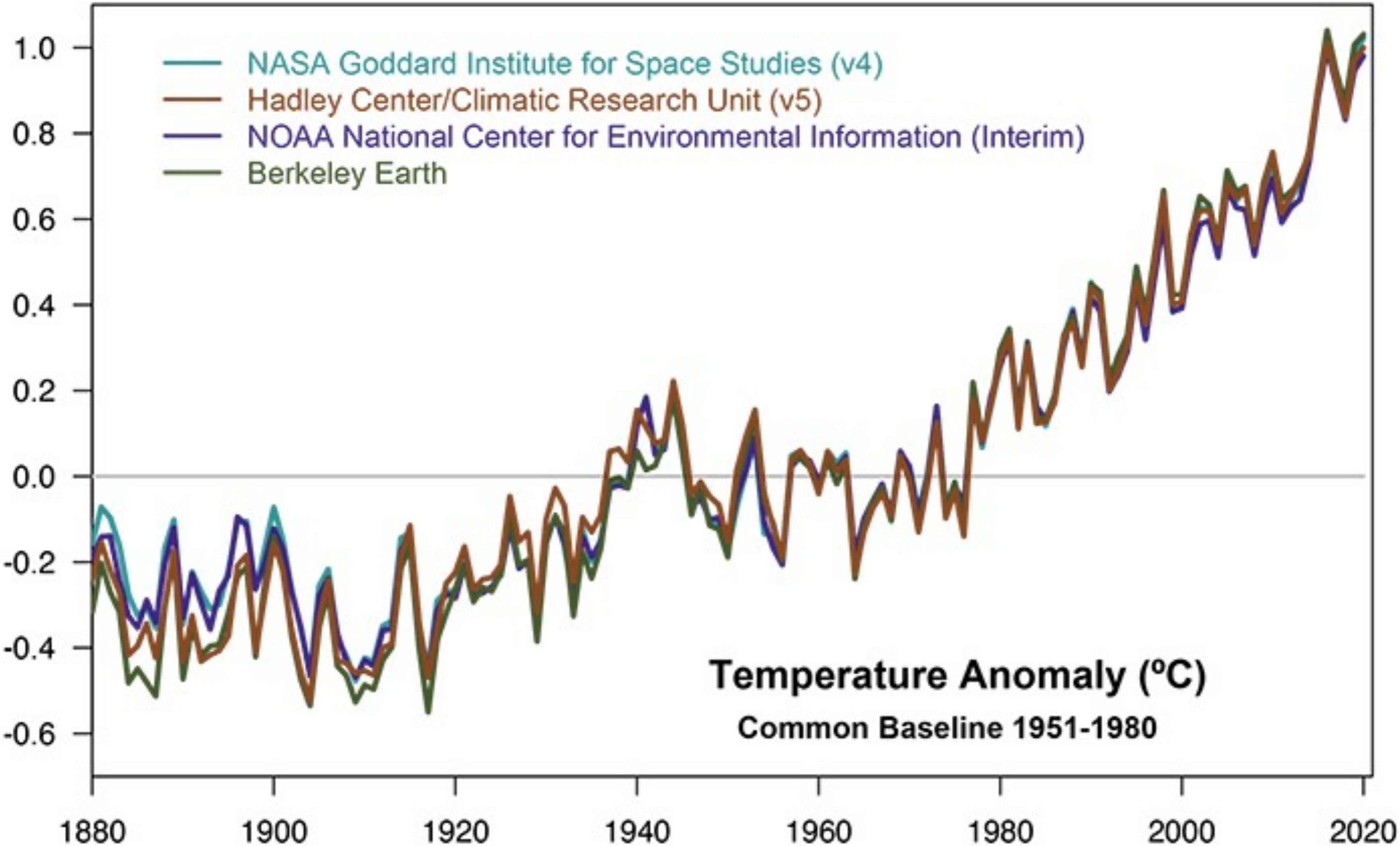
Glaciers on Tian Shan Mountains

'Impossible To Save': Scientists Are Watching China's Glaciers Disappear

October 21, 2017 6:39 AM ET

Weather stations across the world record temperatures of air, land, and ocean

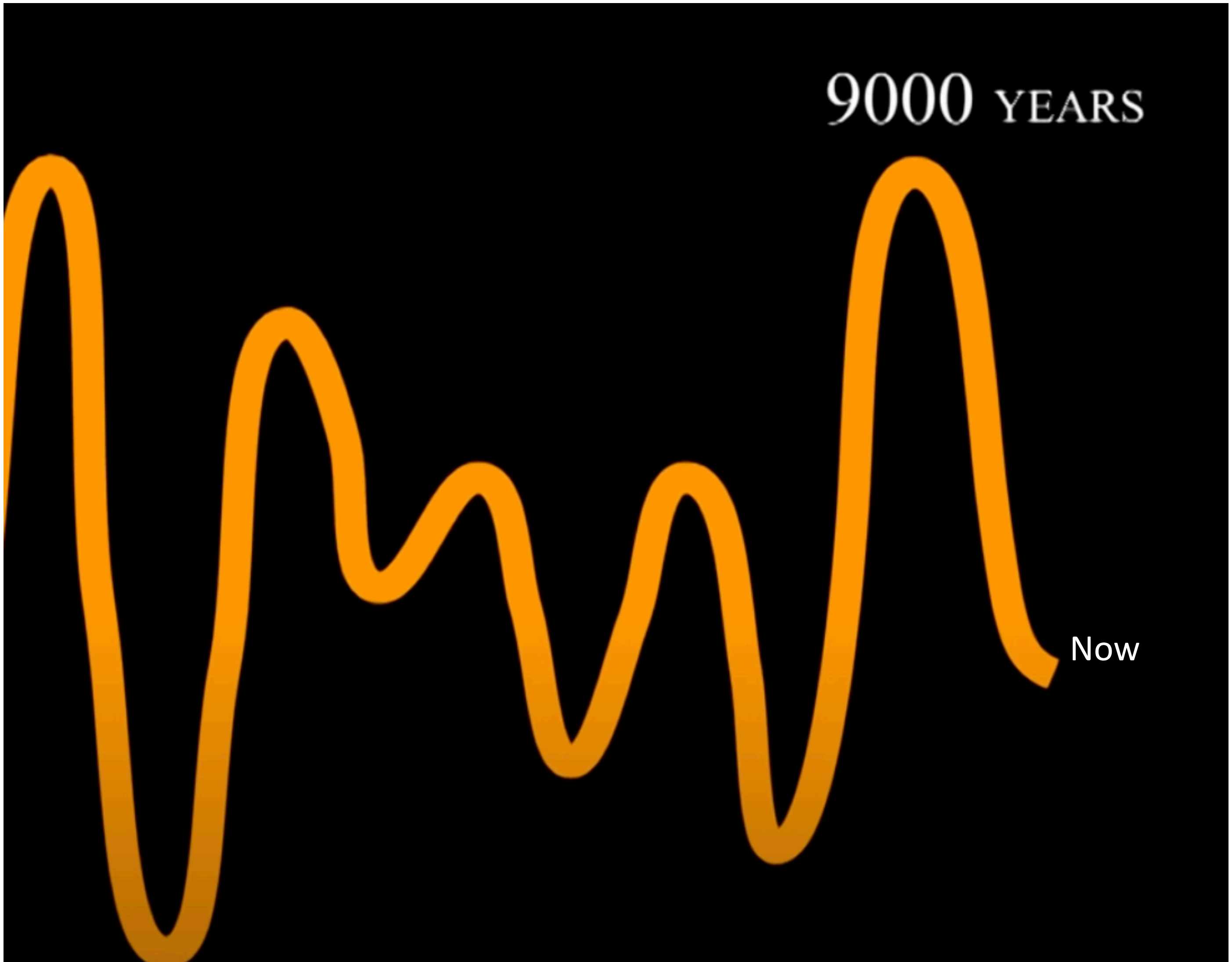
Weather station data since 1880 CE



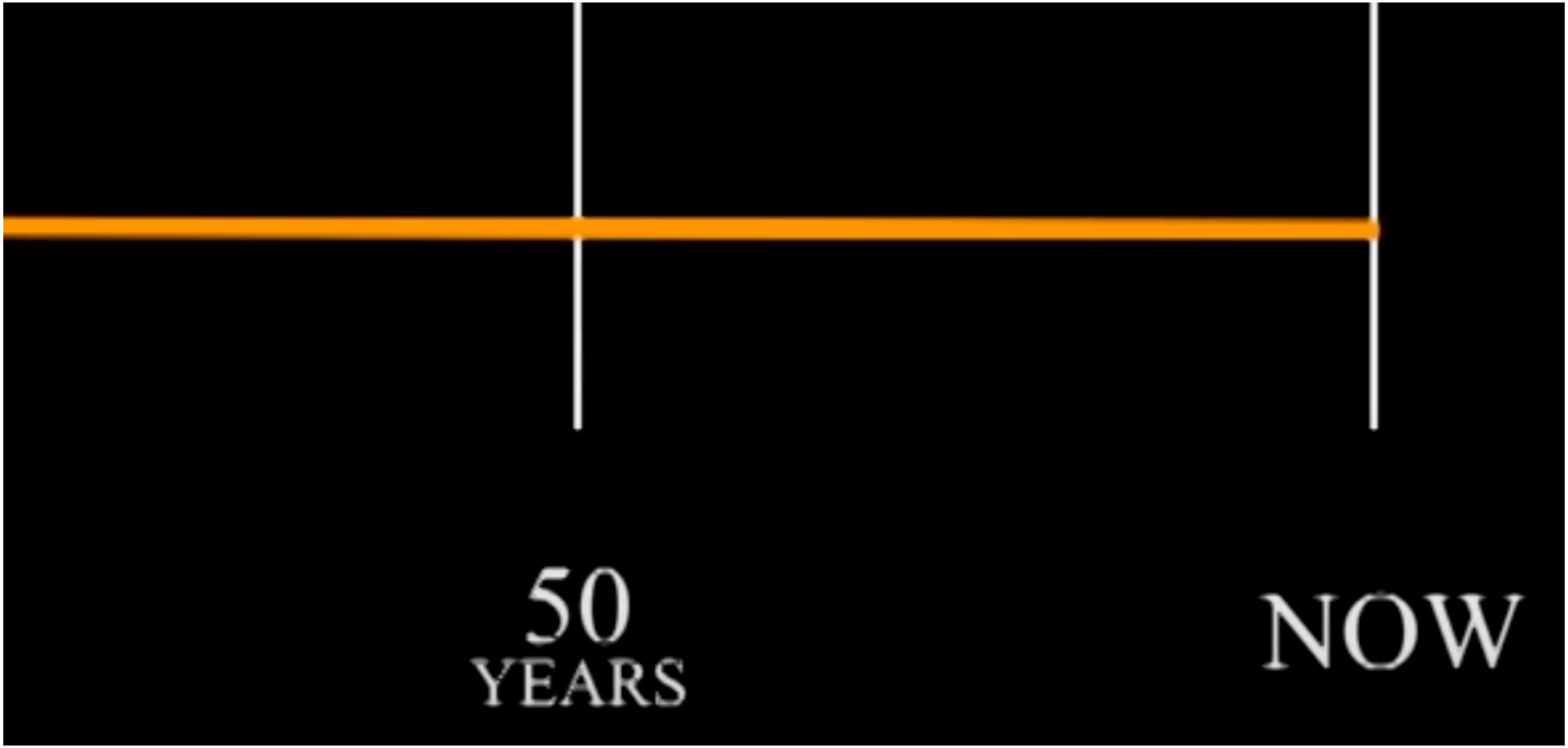
Where are we now in the Cycle?

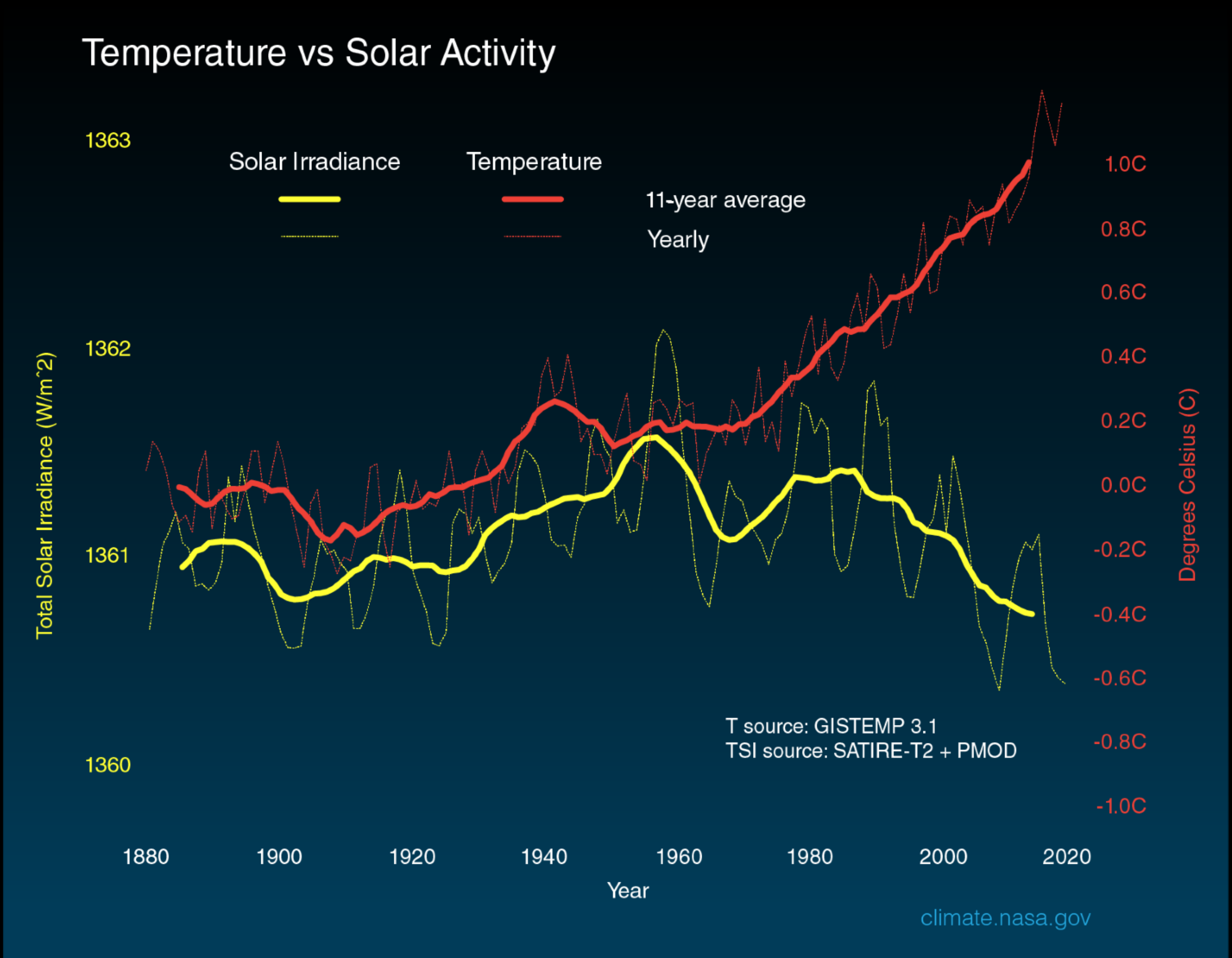
Obliquity: Intermediate and decreasing, Northern Summer at Aphelion

-> Lower Insolation in N hemisphere -> Less snow melt in N summer -> Colder climate



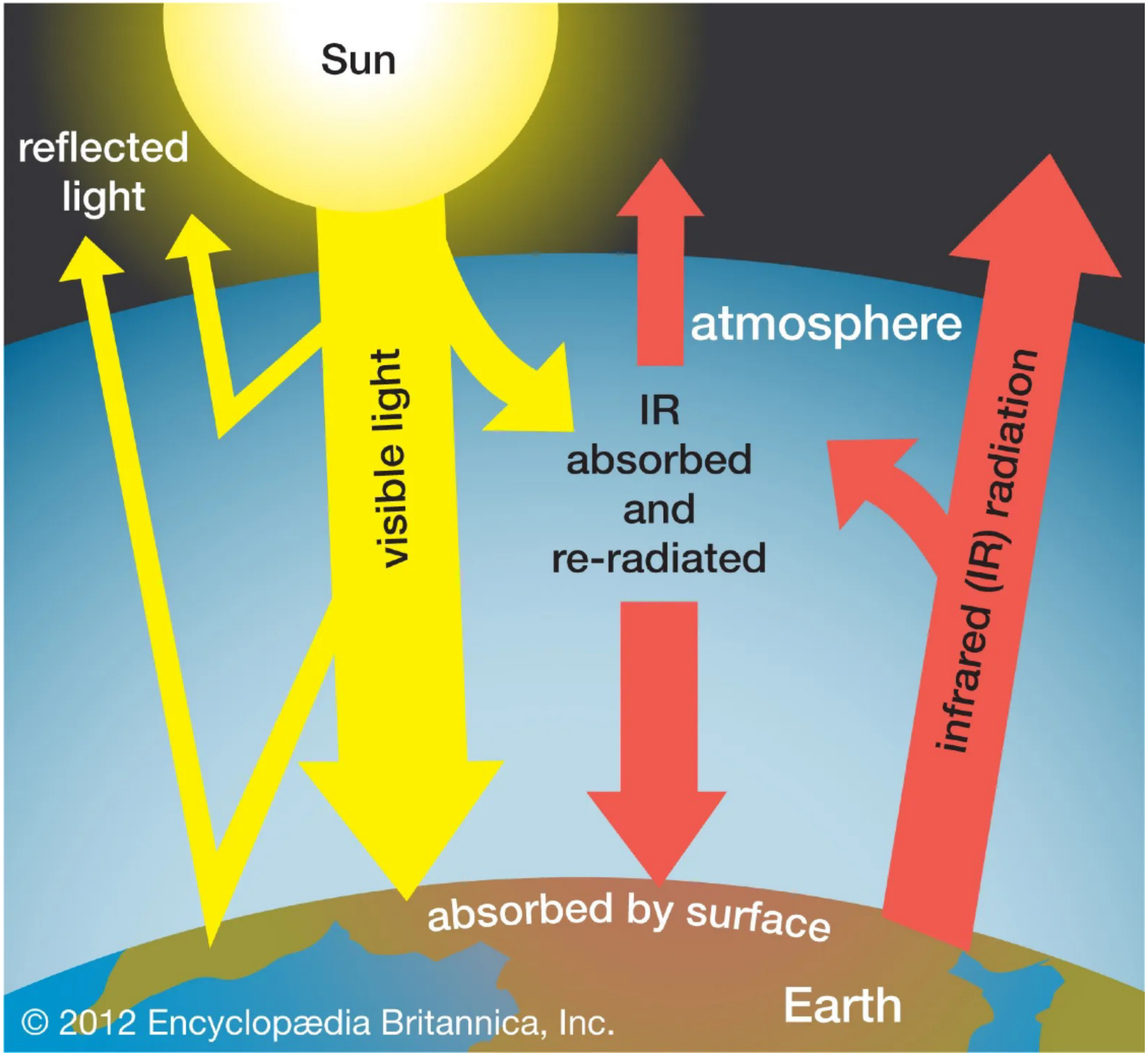
If we zoom in onto the past 100 years of the Milankovitch insolation curve, no significant change in insolation is predicted

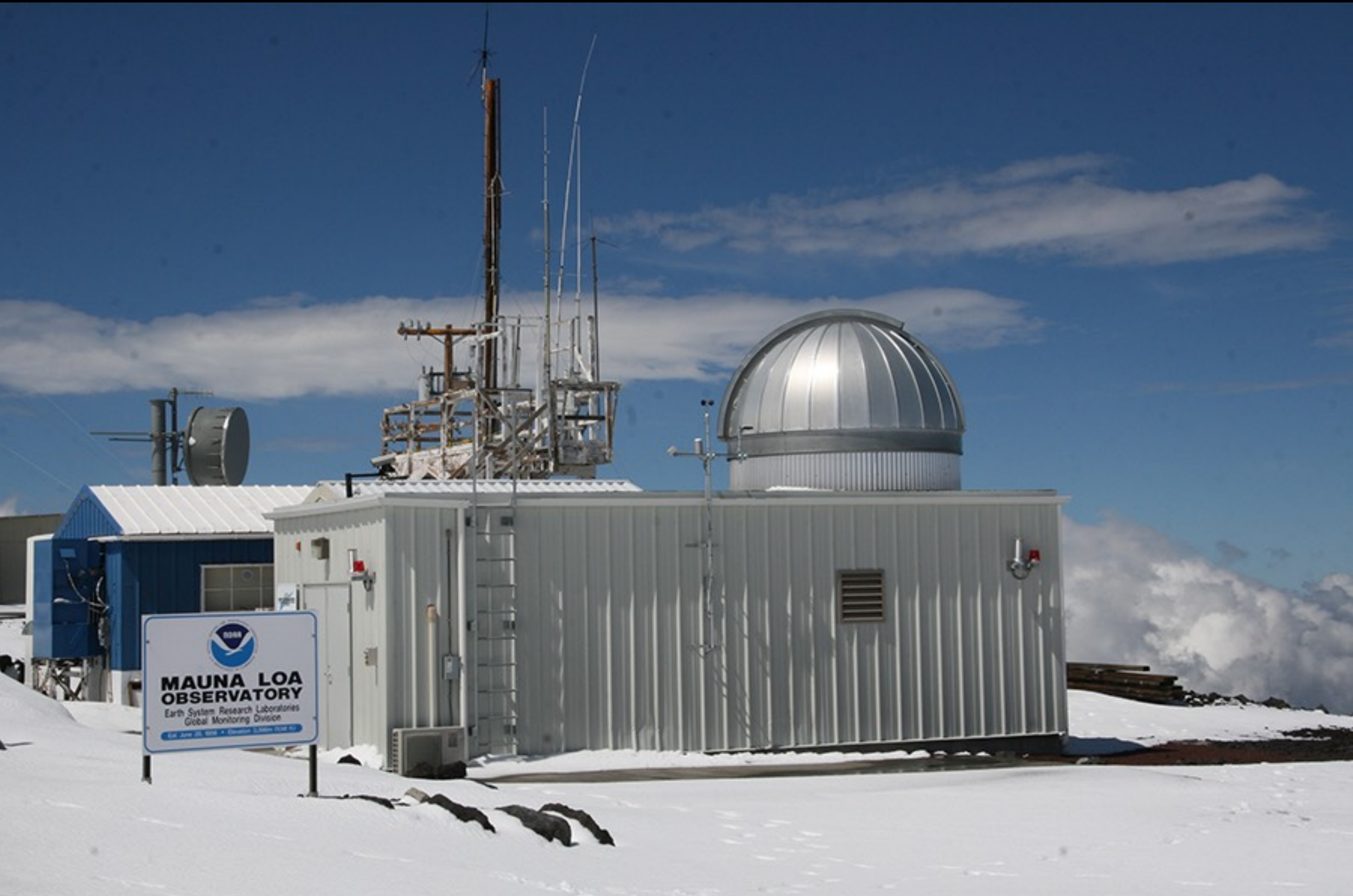




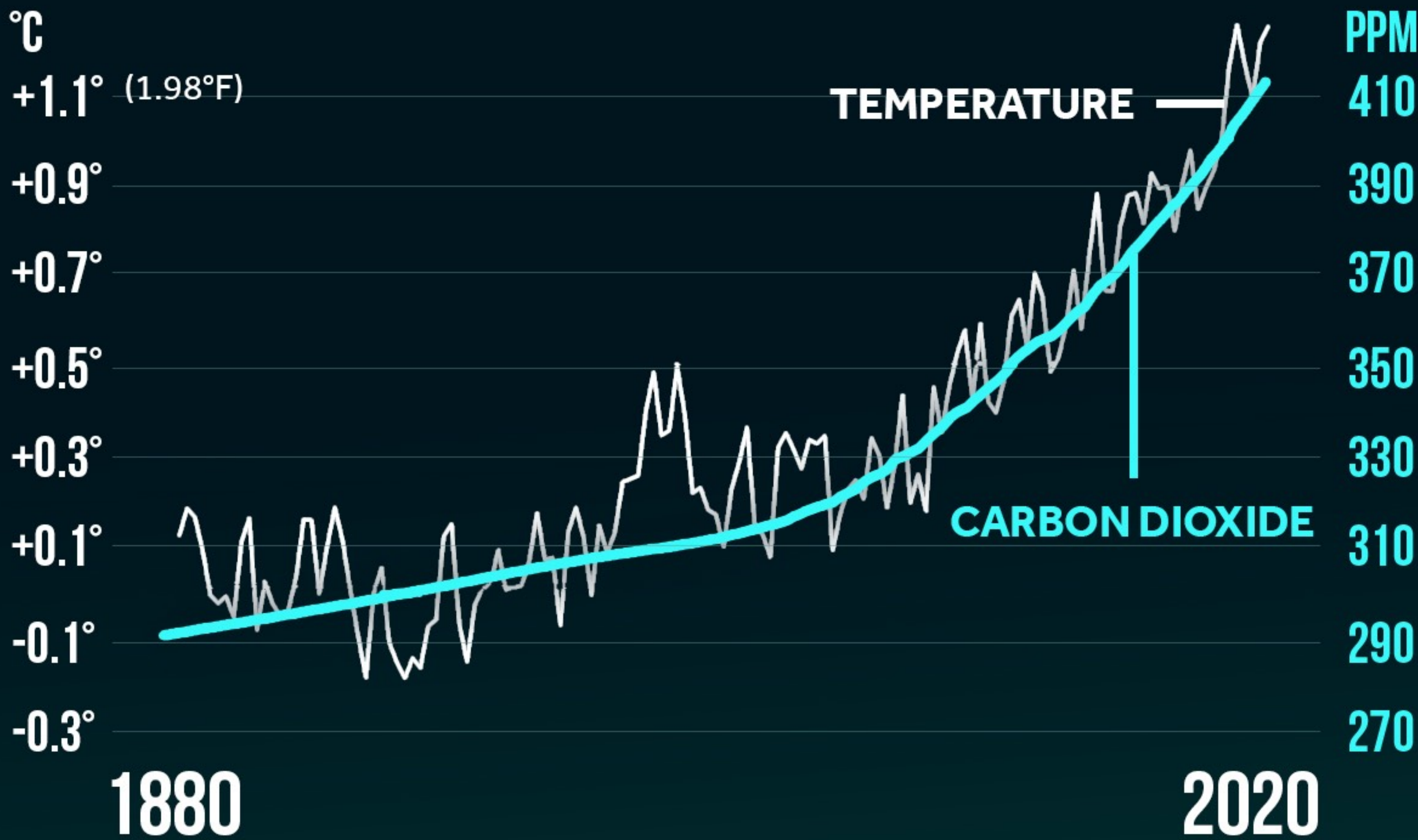
Temperature vs Solar Activity
Solar Irradiance
Temperature
11-year average
Yearly
1363
1362
1361
1360
Total Solar Irradiance (W/m^2)
1.0C
0.8C
0.6C
0.4C
0.2C
0.0C
-0.2C
-0.4C
-0.6C
-0.8C
-1.0C
Degrees Celsius (C)
T source: GISTEMP 3.1
TSI source: SATIRE-T2 + PMOD
1880
1900
1920
1940
1960
1980
2000
2020
Year
climate.nasa.gov

Greenhouse Effect




MAUNA LOA
OBSERVATORY
Earth System Research Laboratories
Global Monitoring Division

GLOBAL TEMPERATURE & CO_2



Global temperature anomalies averaged and adjusted to early industrial baseline (1881-1910)
Global annual average carbon dioxide
Source: NASA GISS, NOAA NCEI, ESRL

CLIMATE CENTRAL

1 deg C = 1.8 deg F

PPM: parts per million

CO2 Level in the past 800 kyrs