Lecture 2: A Modern View of the Universe

Asteroid Ida and satellite Dactyl

Claire Max

April 3rd, 2014

Astro 18: Planets and Planetary Systems

UC Santa Cruz

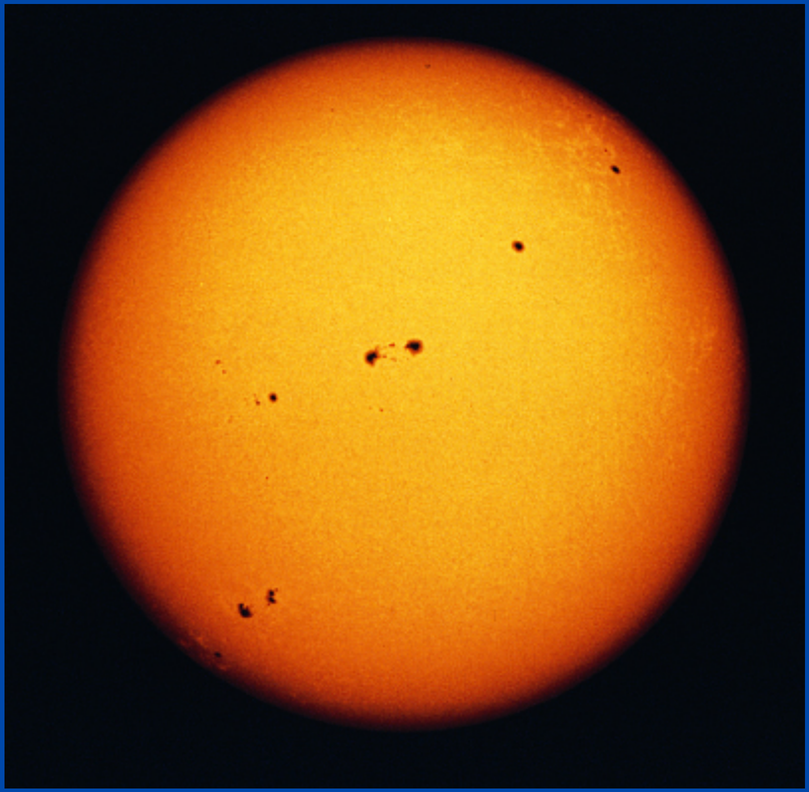
Topics for this class

- Some definitions
- What is our place in the universe?
- Geometry of the Solar System
- The cosmic distance scale
- The expansion of the universe and the Big Bang
- Dark Matter and Dark Energy

Please remind me
to take break at
12:45

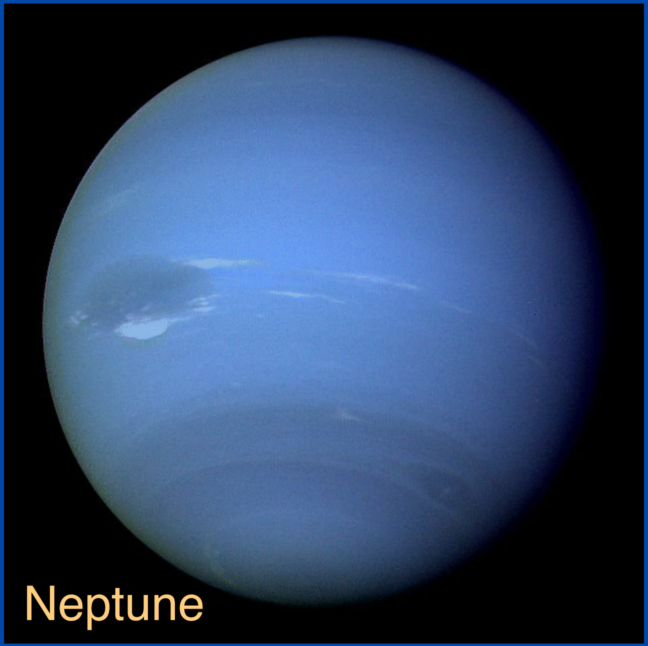
What is a Star?

- A large, glowing ball of gas that generates heat and light through nuclear fusion



- Nuclear Fusion:
  - Energy generation mechanism in which two light atoms join together (fuse) to form a heavier atom

1. Planet: Intuitive Definition



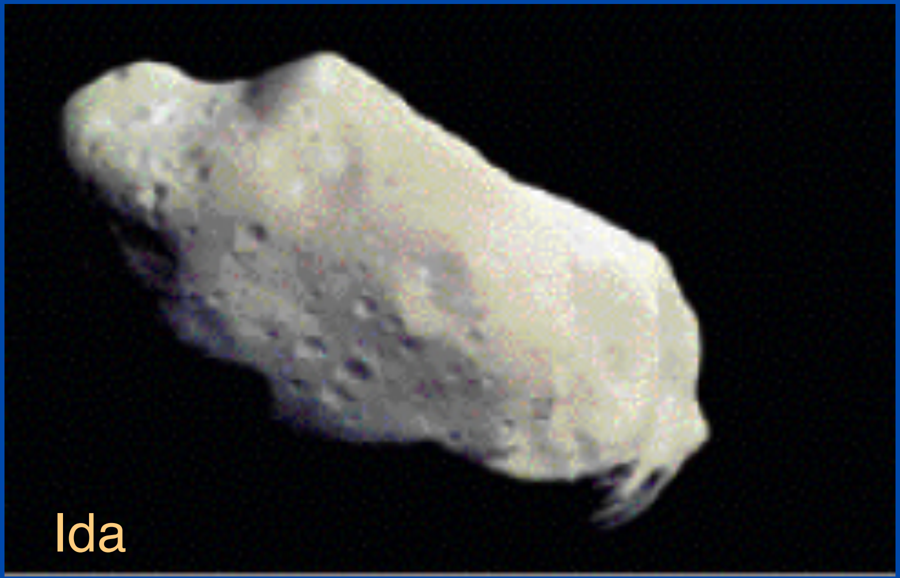
- A moderately large object that orbits a star.
- It shines mostly by reflected light from its parent star.

2. Planet: International Astronomical Union Definition

- A celestial body that
  - (a) is in orbit around the Sun
  - (b) has sufficient mass for its self-gravity to overcome rigid body forces, so that it assumes a hydrostatic equilibrium (nearly round) shape, and
  - (c) has cleared the neighbourhood around its orbit.
- Note that by design, this definition only applies to planets in our Solar System. Definition of planets in other Solar Systems was postponed until future deliberations of the IAU.

Asteroid

A relatively small and rocky object that orbits a star.



Moon (or satellite)

Ganymede (orbits Jupiter)

a) An object that orbits a planet

b) An object that orbits another Solar System object

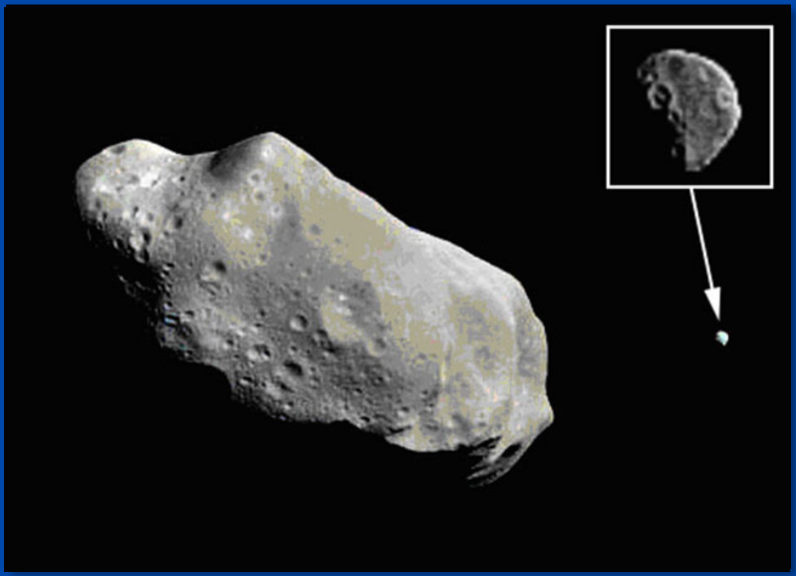
Dactyl (orbits the asteroid Ida)

Moon (or satellite)

Ganymede (orbits Jupiter)

a) An object that orbits a planet

b) An object that orbits another Solar System object

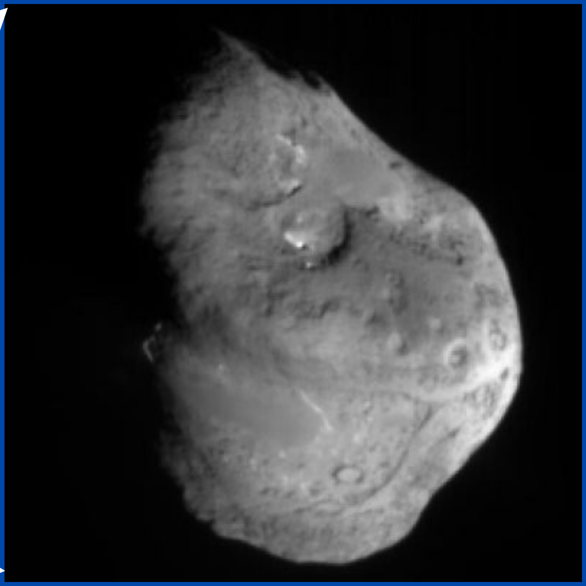


Dactyl (orbits the asteroid Ida)

Comet

Tail (gas and dust)

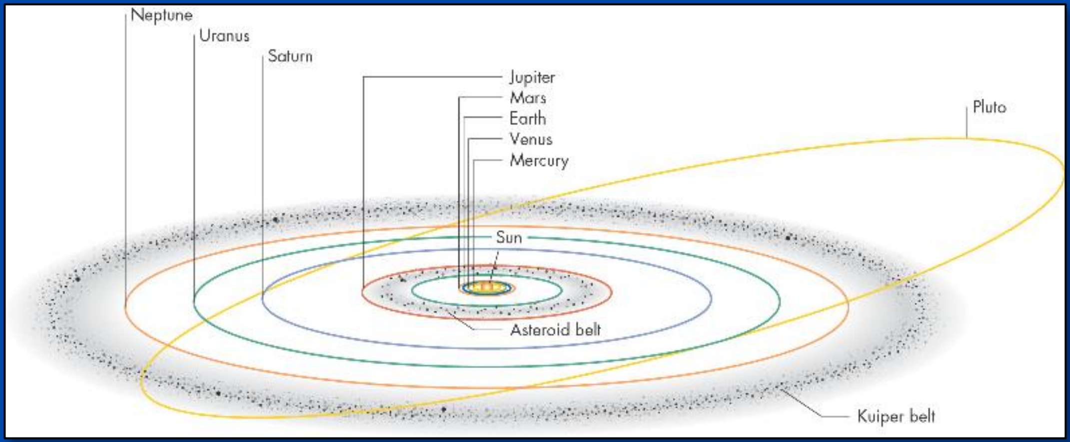
A relatively small and icy object that orbits a star.



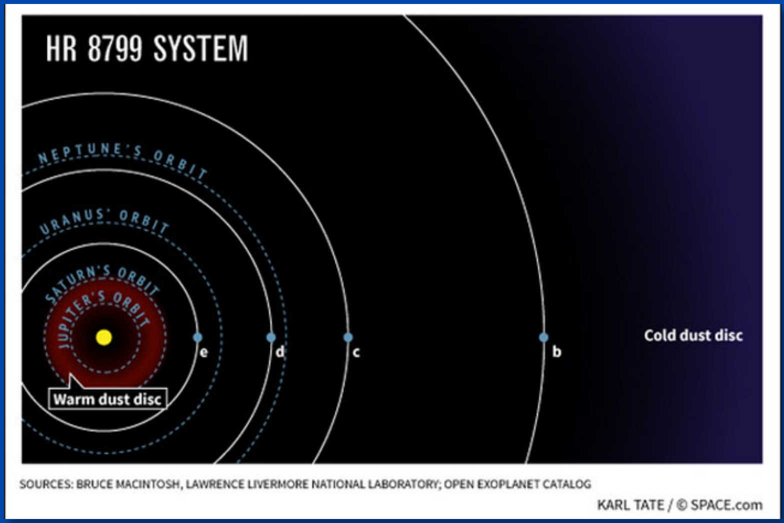
Comet nucleus

Solar (Star) System

- **A star and all the material that orbits it, including its planets, moons, asteroids, comets**



Credit: O'Connell, U Va.



Galaxy

- A very large grouping of stars in space, held together by gravity and orbiting a common center.
- Masses: 10^7 - 10^{13} times the mass of our Sun

Our Milky Way Galaxy

Under the River of Stars © Serge Brunier

The Universe

- The sum total of all matter and energy: everything within and between all galaxies

Notation: Orders of magnitude

- 10^2 = 100 = 1 with 2 zeros after it
- 10^3 = 1000 = 1 with 3 zeros after it
- 10^9 = 1 with 9 zeros after it = 1 billion
- 10^{11} = 1 with 11 zeros after it = 100 billion

How big is the (observable) Universe?

- ***The Milky Way is one of about 100 billion galaxies***
- ***10^{11} stars/galaxy x 10^{11} galaxies = 10^{22} stars in the universe***

As many stars as grains of (dry) sand on *all* Earth's beaches…

Thought Question

Suppose you tried to count the more than 100 billion stars in our galaxy, at a rate of one per second…

How long would it take you?

A. a few weeks

B. a few months

C. a few years

D. a few thousand years

How did I know this?

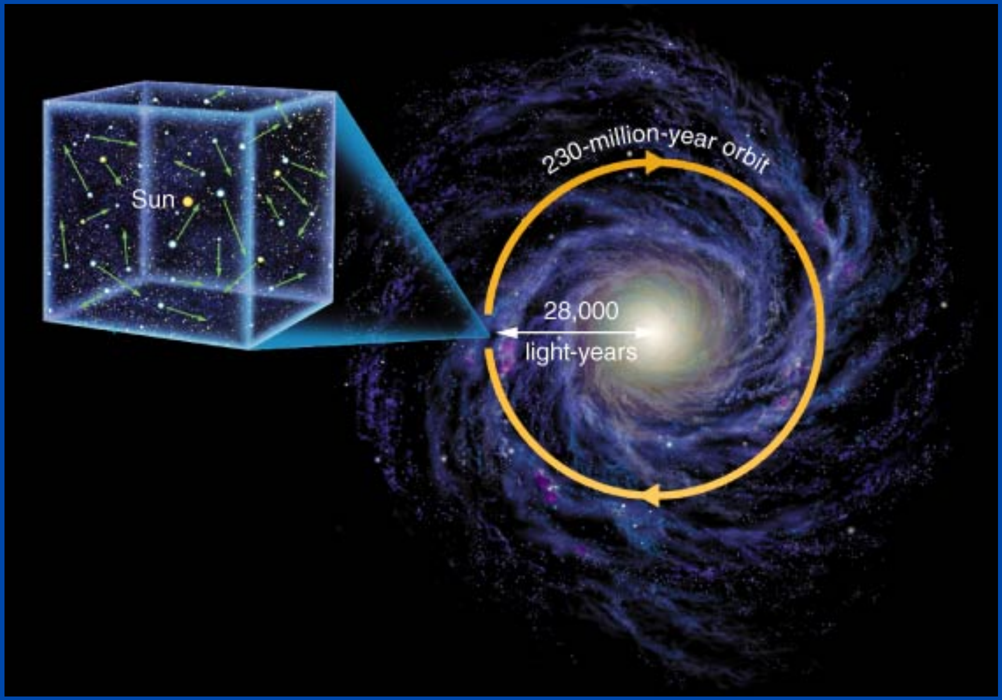
- **A year has about 3 x 10^7 seconds**
- **100 billion stars = 10^{11} stars**

$$10^{11}\ \cancel{\text{stars}} \times \frac{1\ \cancel{\text{sec}}}{\cancel{\text{star}}} \times \frac{1\ \text{year}}{3\times 10^{7}\ \cancel{\text{sec}}} \approx \frac{10^{11}}{3\times 10^{7}}\,\text{years} \approx \left(\frac{10}{3}\right)\times 10^{3}\,\text{years}$$

or "a few thousand years"

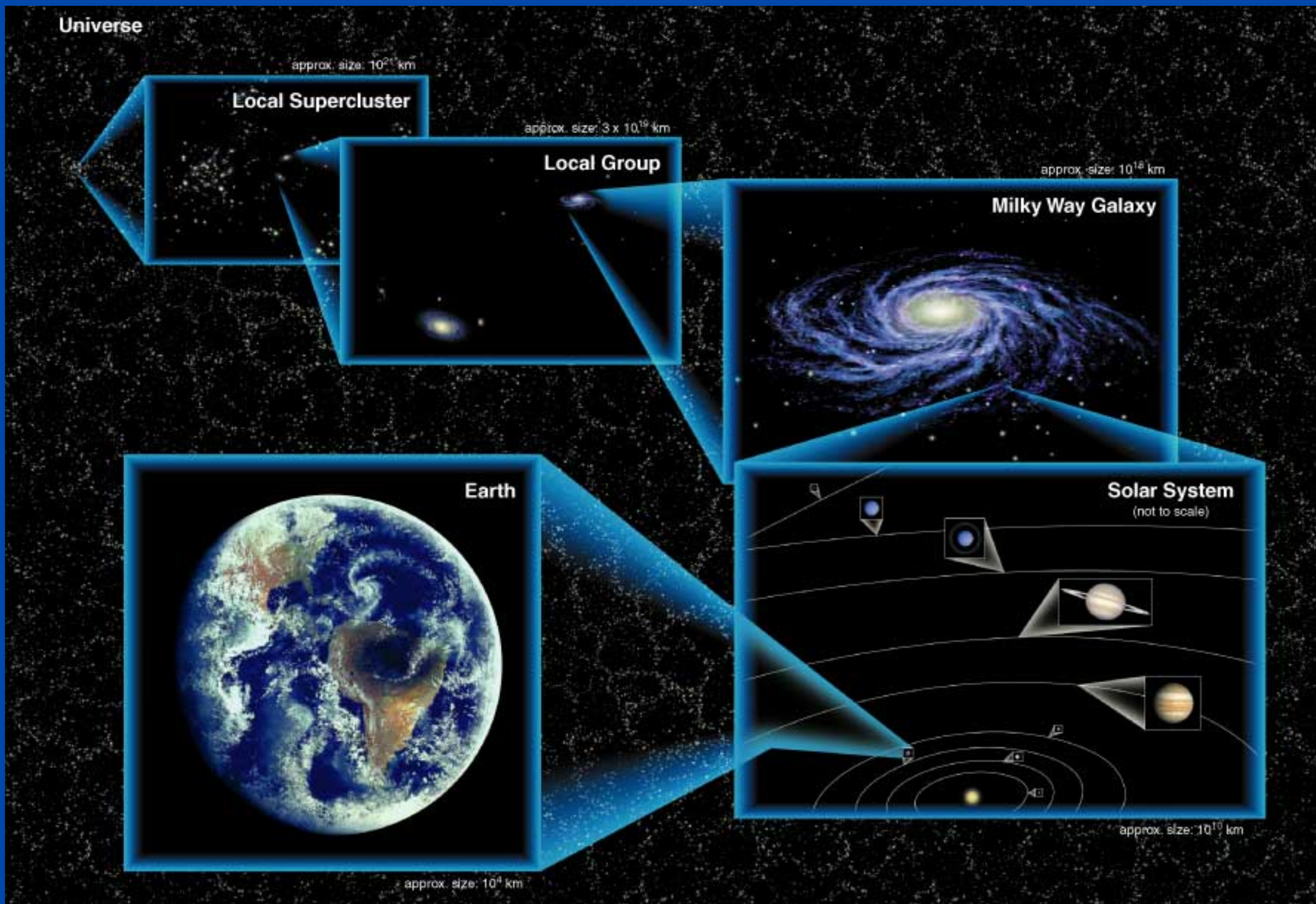
Our Sun moves randomly relative to the other stars in the local Solar neighborhood…

- … and orbits the galaxy every 230 million years.



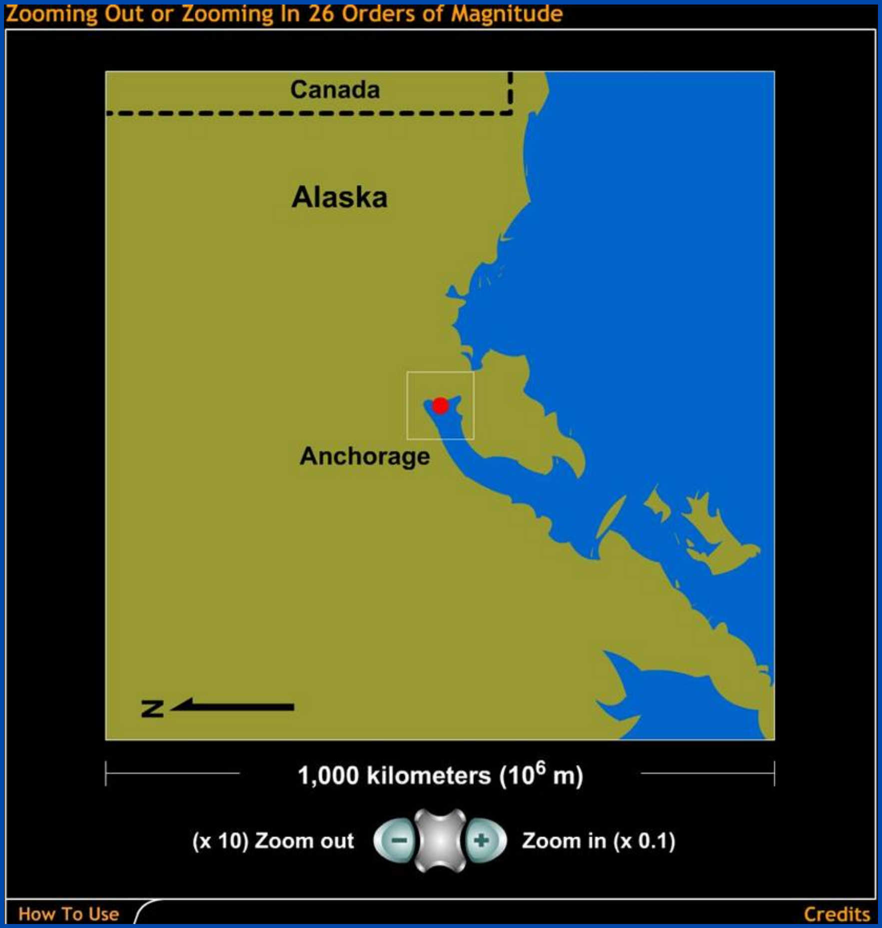
- Typical relative speeds of > 70,000 km/hr (!)
- But stars are so far away that we can't easily notice their motion

Our place in the universe



How big is the universe?

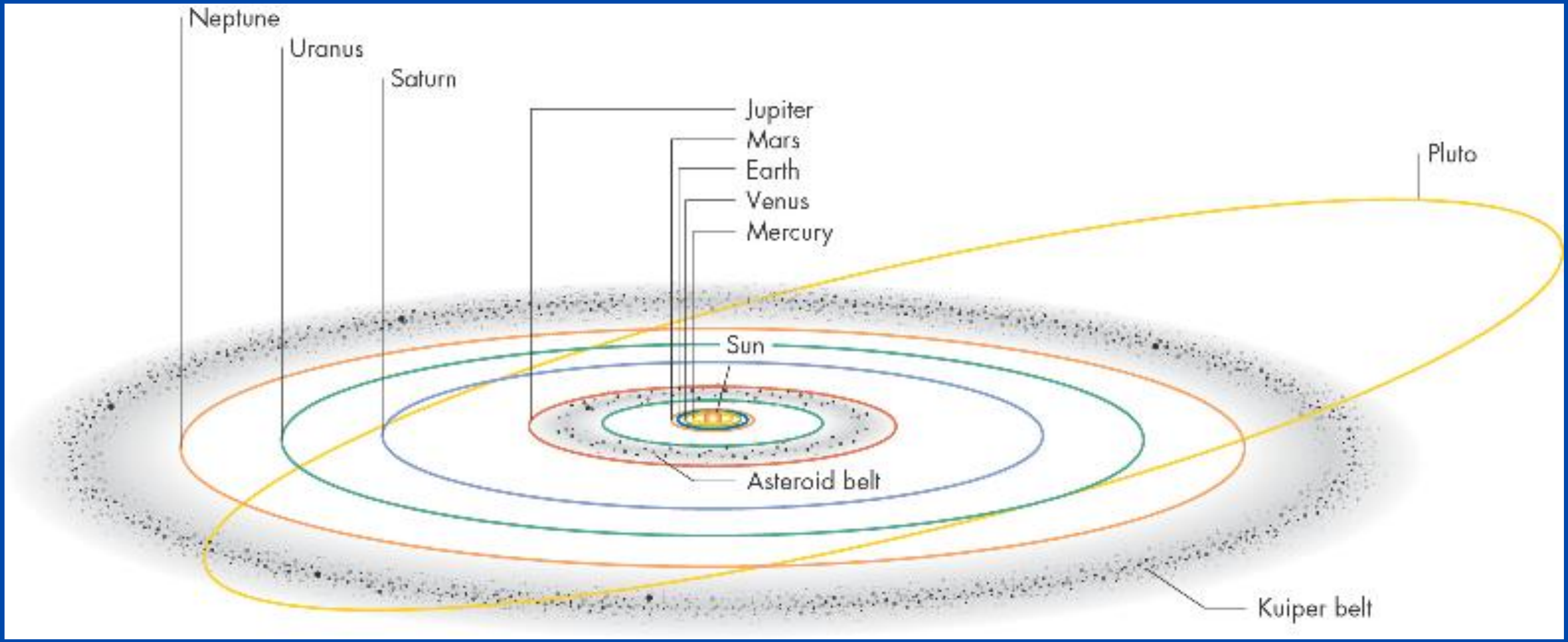
- Let's step through the universe in powers of 10:



Interactive Figure

Geometry of the Earth relative to the Solar System

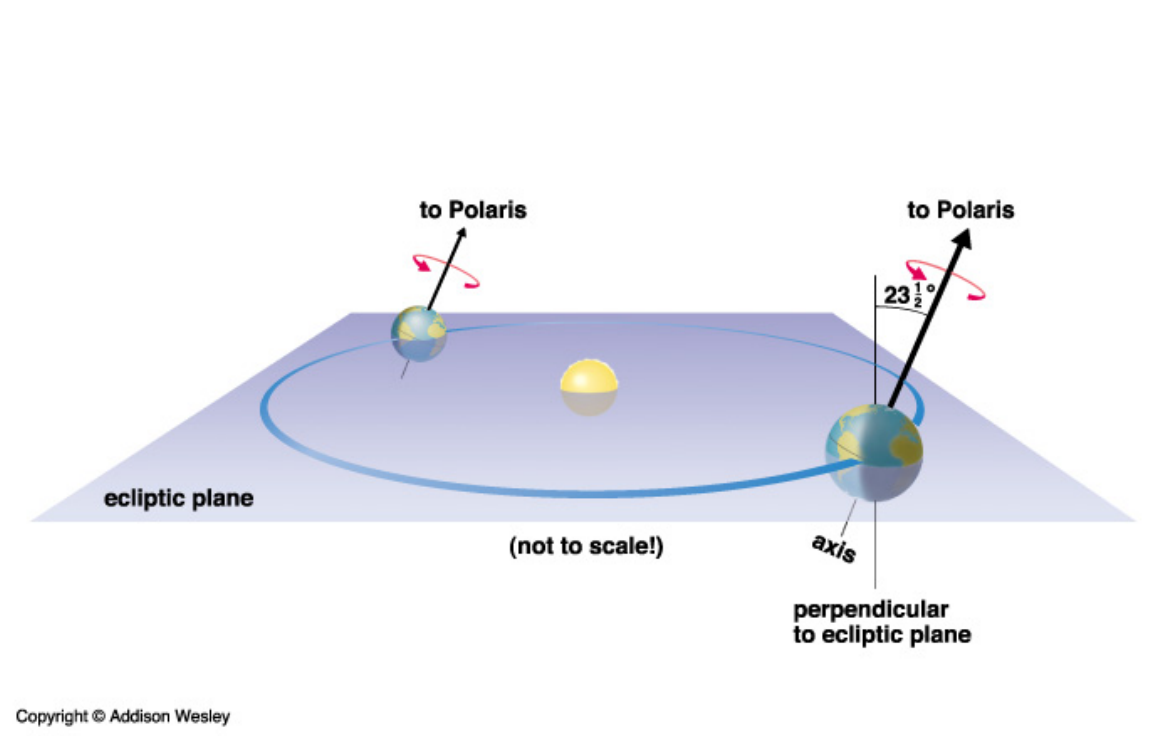
- **The Sun and all the planets except Pluto lie in a "plane" called the "Ecliptic plane"**



Credit: O'Connell, U Va.

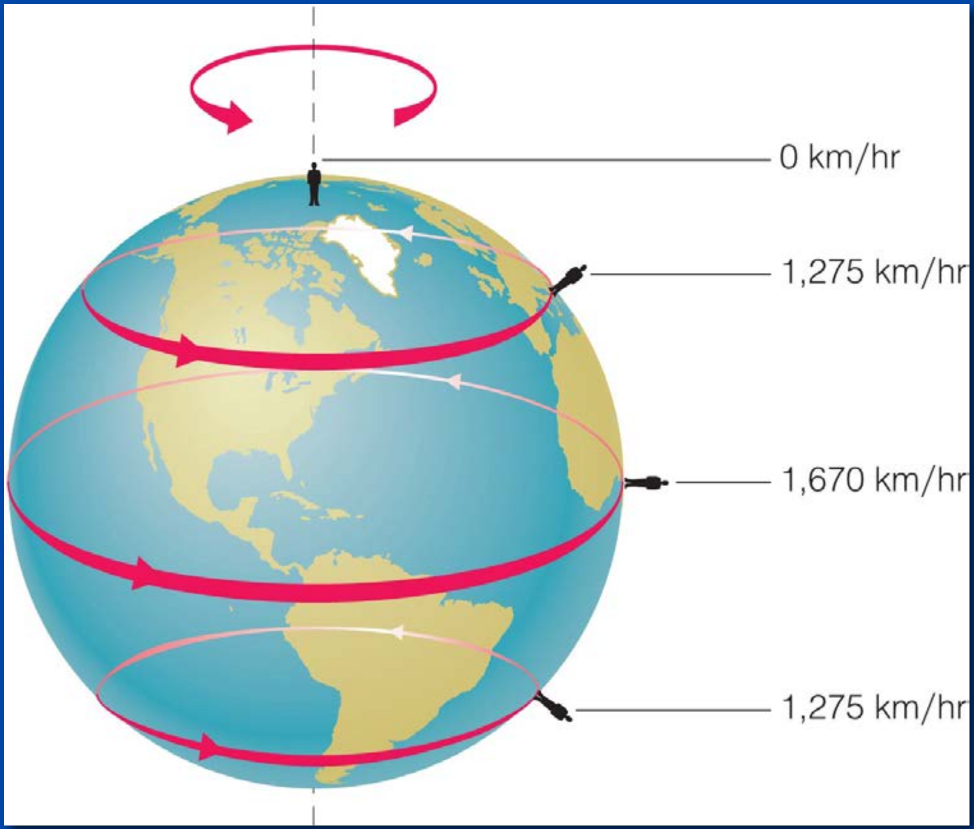
But Earth's rotation axis is <u>not</u> perpendicular to this plane

- **Earth's rotation axis is inclined at 23.5 degrees**
- **North rotational pole points to the North Star, Polaris**



Note that both rotation and motion around Sun are counter-clockwise, if you are looking from above the N pole

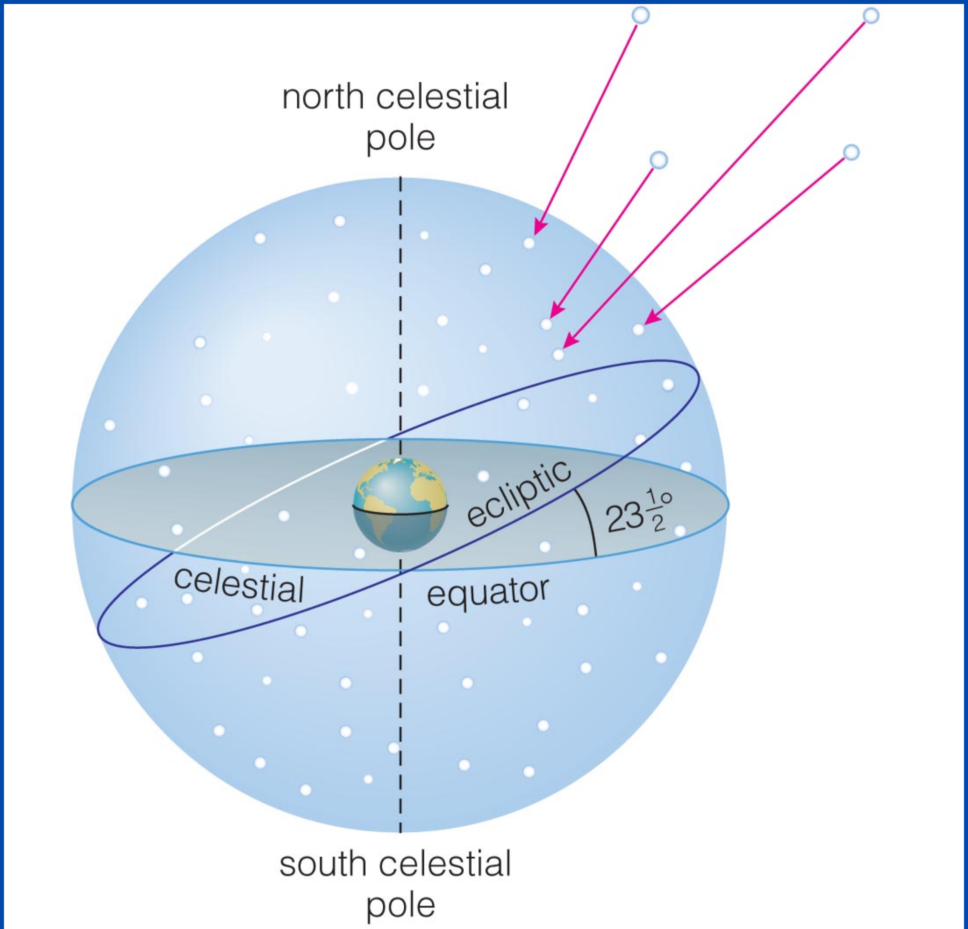
How is Earth moving in our solar system?



- **Contrary to our perception, we are not "sitting still."**
- **We are moving with the Earth in several ways, and at surprisingly fast speeds…**

The Earth **rotates** around its axis once every day.

The "Celestial Sphere"

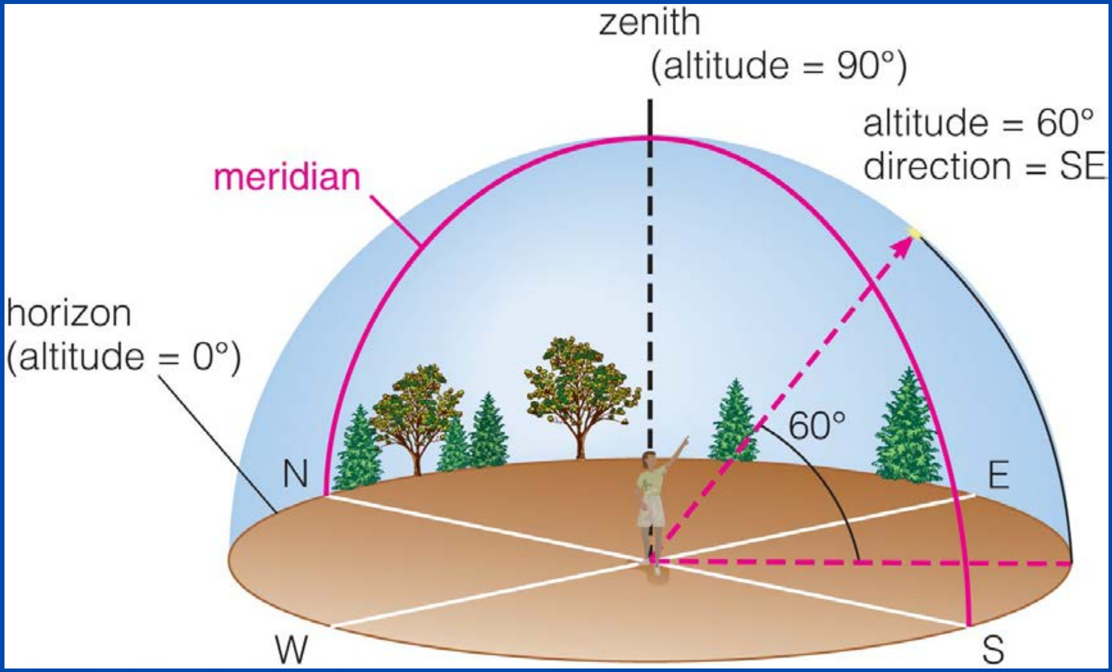


Stars at different distances all <u>appear</u> to lie on the "celestial sphere."

***Ecliptic* is Sun's apparent path through the celestial sphere.**

Because our Solar System lies almost in a plane, planets follow paths along ecliptic as well.

The Local Sky



Zenith: The point directly overhead

Horizon: All points 90° away from zenith

Meridian: Line passing through zenith and connecting N and S points on horizon

Results of the tilt of Earth's axis

- Seasons

- Apparent motions of stars in sky
  - and how these vary with where you are on the Earth

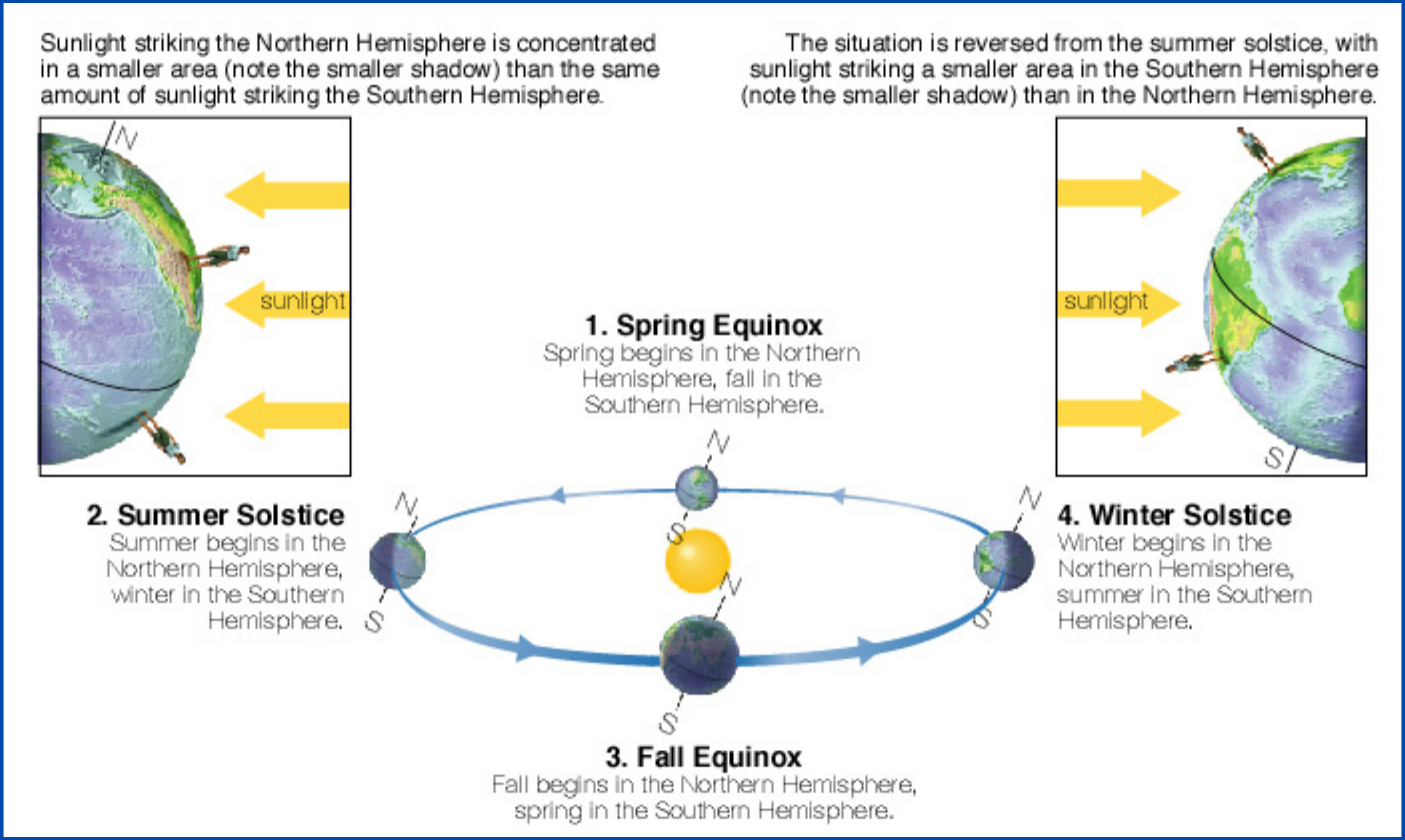
- Apparent paths of planets and Sun along the ecliptic

- Precession of the Earth's axis
  - in 15,000 AD, the "North Star" won't be Polaris any more, it will be Vega (the brightest star in the Summer Triangle)

Seasons: Key concepts

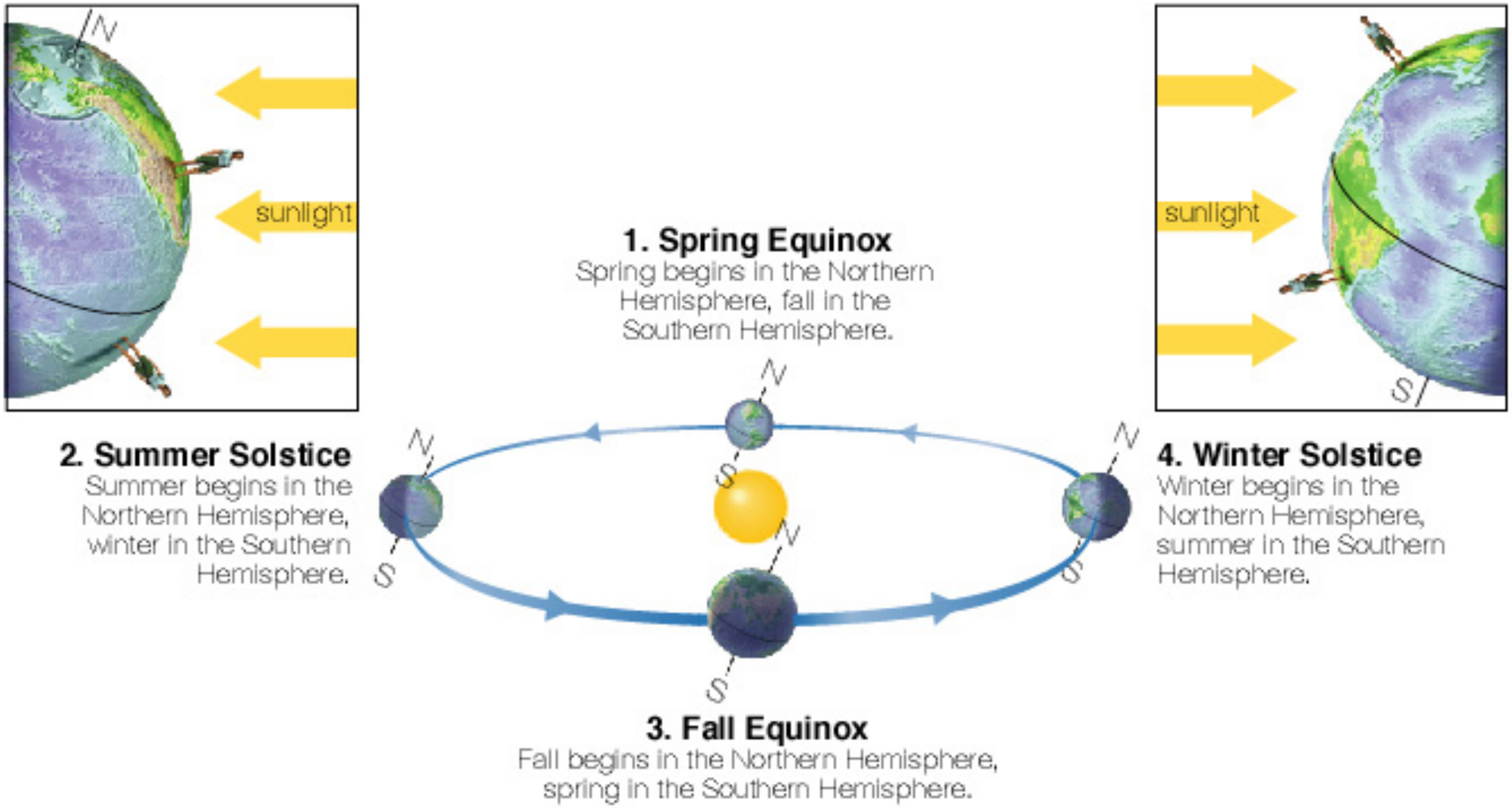
- Earth's rotation axis is tilted with respect to its orbital plane
- Tilt angle changes the angle of sunlight striking the Earth's surface
- At a fixed location on the Earth, the angle of the sunlight varies with time
- Seasons!
- Other planets have different tilts, and thus different types of seasons

Seasons: summer is when your hemisphere is tipped toward Sun

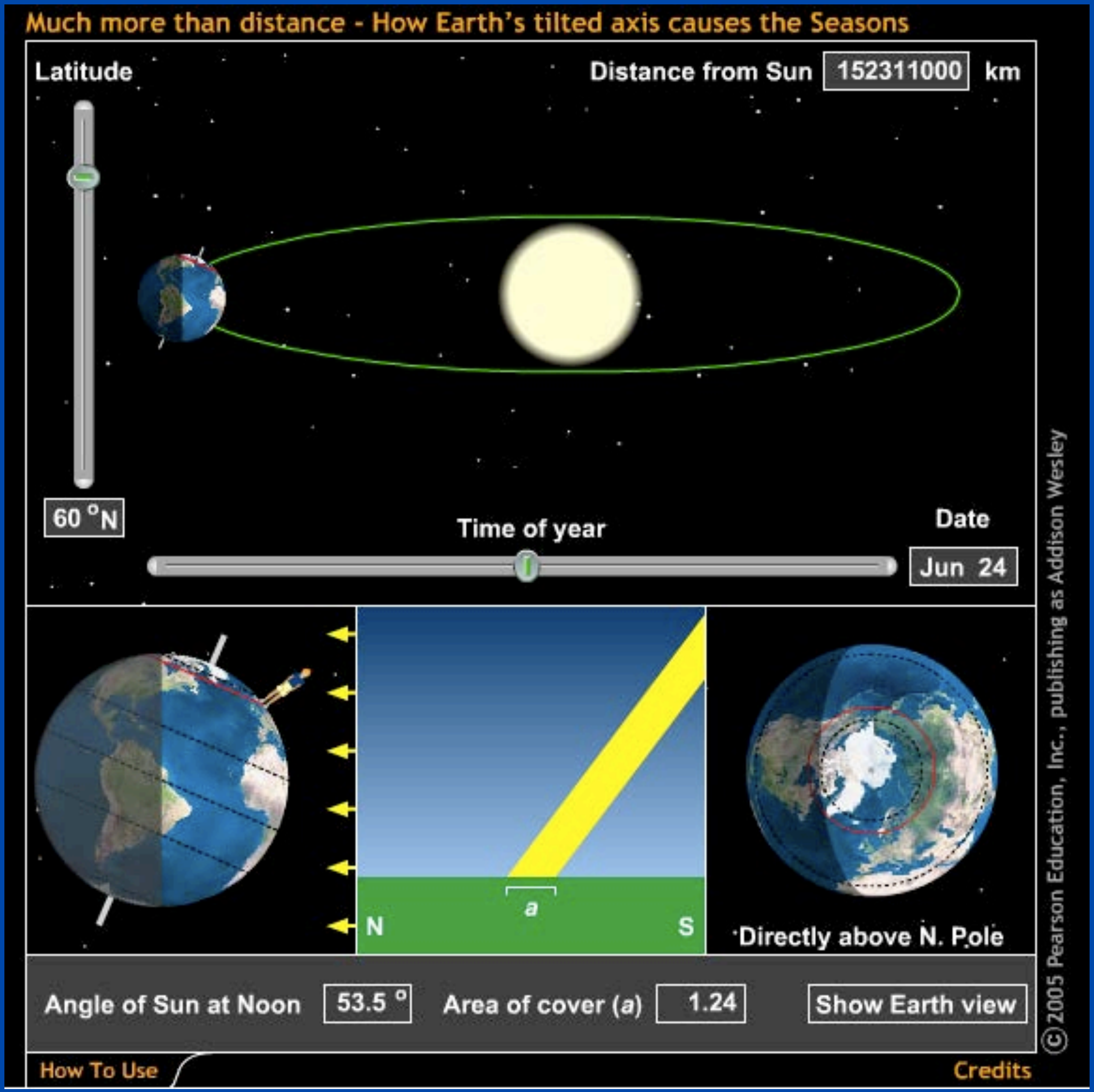


Seasons: summer is when your hemisphere is tipped toward Sun

Note: Earth is <u>closest</u> to Sun in January, farthest in July!



What causes the seasons, cont'd

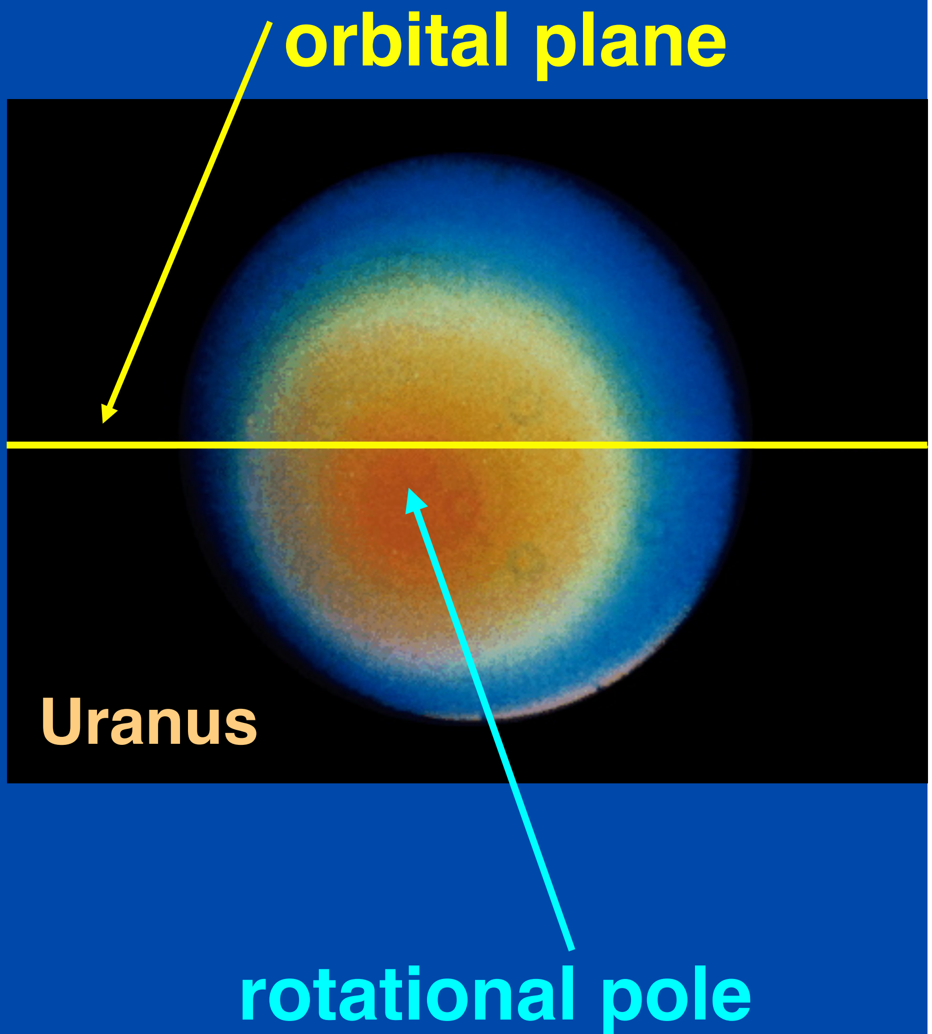


Tilt of Earth's axis causes sunlight to be spread out differently in summer and winter

Click here

Most extreme seasons in Solar System: Uranus has a 42-year summer!

- Uranus is tipped on its side:
  - Rotation axis lies almost in its orbital plane
- Uranus takes 84 Earth-years to go around the Sun
- So the North polar regions of Uranus have summer (in this case, continuous sunlight) for 42 Earth-years!



ConcepTest

I will pose a question on next slide.

First, each of you will have one minute to think about the answer (three multiple choices). This is not a trick question: think conceptually.

Then, break into groups of 2 or 3

You will have two minutes to convince your neighbors of the best answer. Discuss!

I will then ask for a show of hands for the three multiple choices, and we will discuss the results.

ConcepTest

You are having an argument with a friend about what causes Earth's seasons. Your friend insists the difference between summer and winter is that the Earth is closer to the Sun in summer. Which of the following is the best fact you can use to convince your friend that his/her explanation must be wrong? Why?

a) days are shorter in winter than in summer

b) if you are above the Arctic Circle in winter, there is a long period of time when the sun never rises

c) when it is winter in the Northern Hemisphere, it is summer in the Southern Hemisphere

ConcepTest

You are having an argument with a friend about what causes Earth's seasons. Your friend insists the difference between summer and winter is that the Earth is closer to the Sun in summer. Which of the following is the best fact you can use to convince your friend that his/her explanation must be wrong? Why?

a) days are shorter in winter than in summer

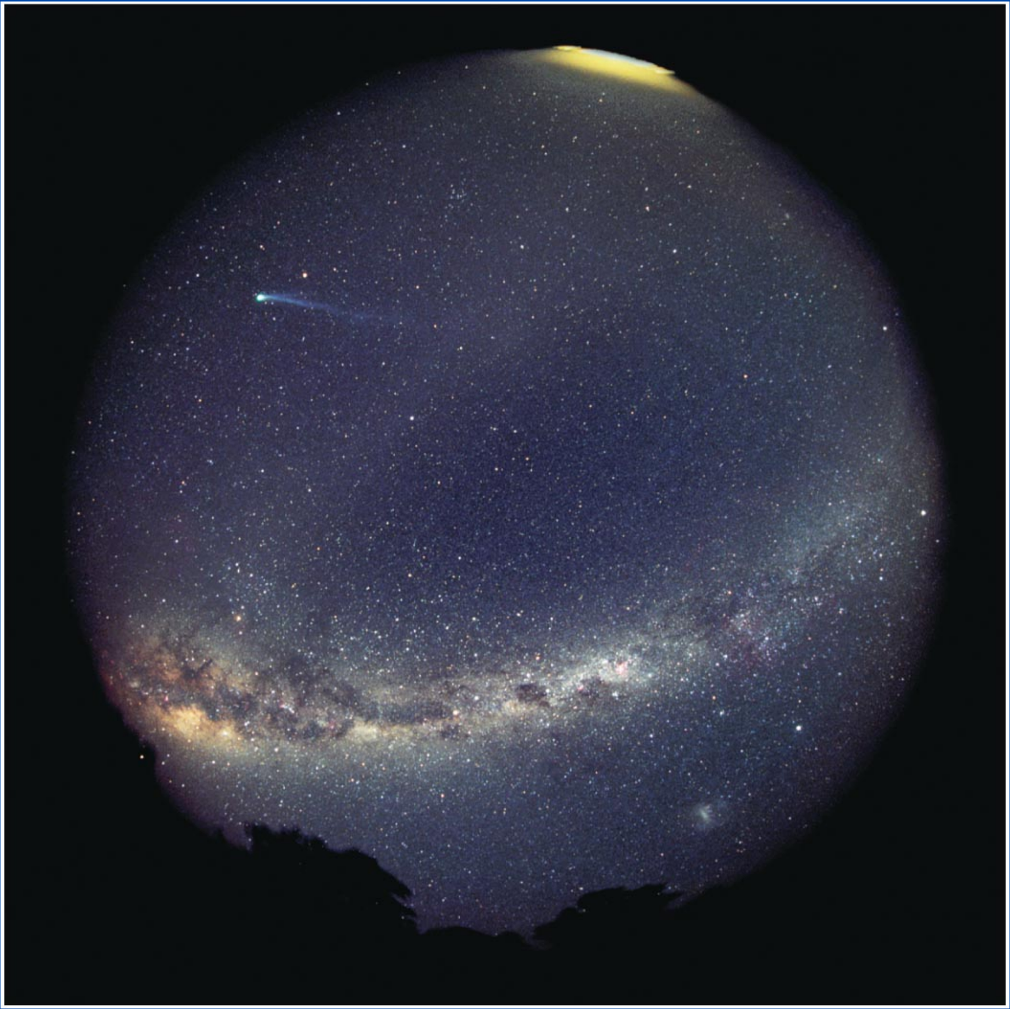
b) if you are above the Arctic Circle in winter, there is a long period of time when the sun never rises

c) when it is winter in the Northern Hemisphere, it is summer in the Southern Hemisphere

What does the universe look like from Earth?

With the naked eye, we can see more than 2,000 stars as well as the Milky Way (the plane of our Galaxy).

All the stars we see with our naked eyes are in our own Galaxy



With a telescope, we can see distant galaxies in long time exposures

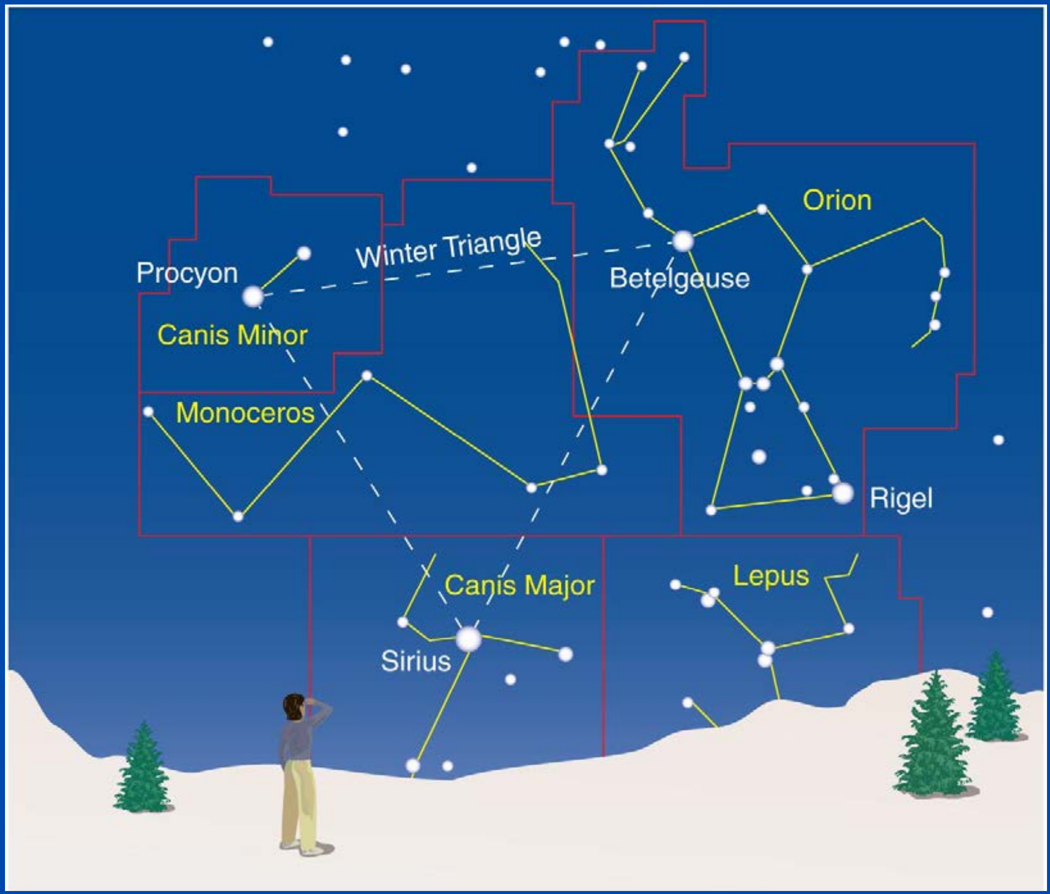
Hubble Space Telescope

Constellations

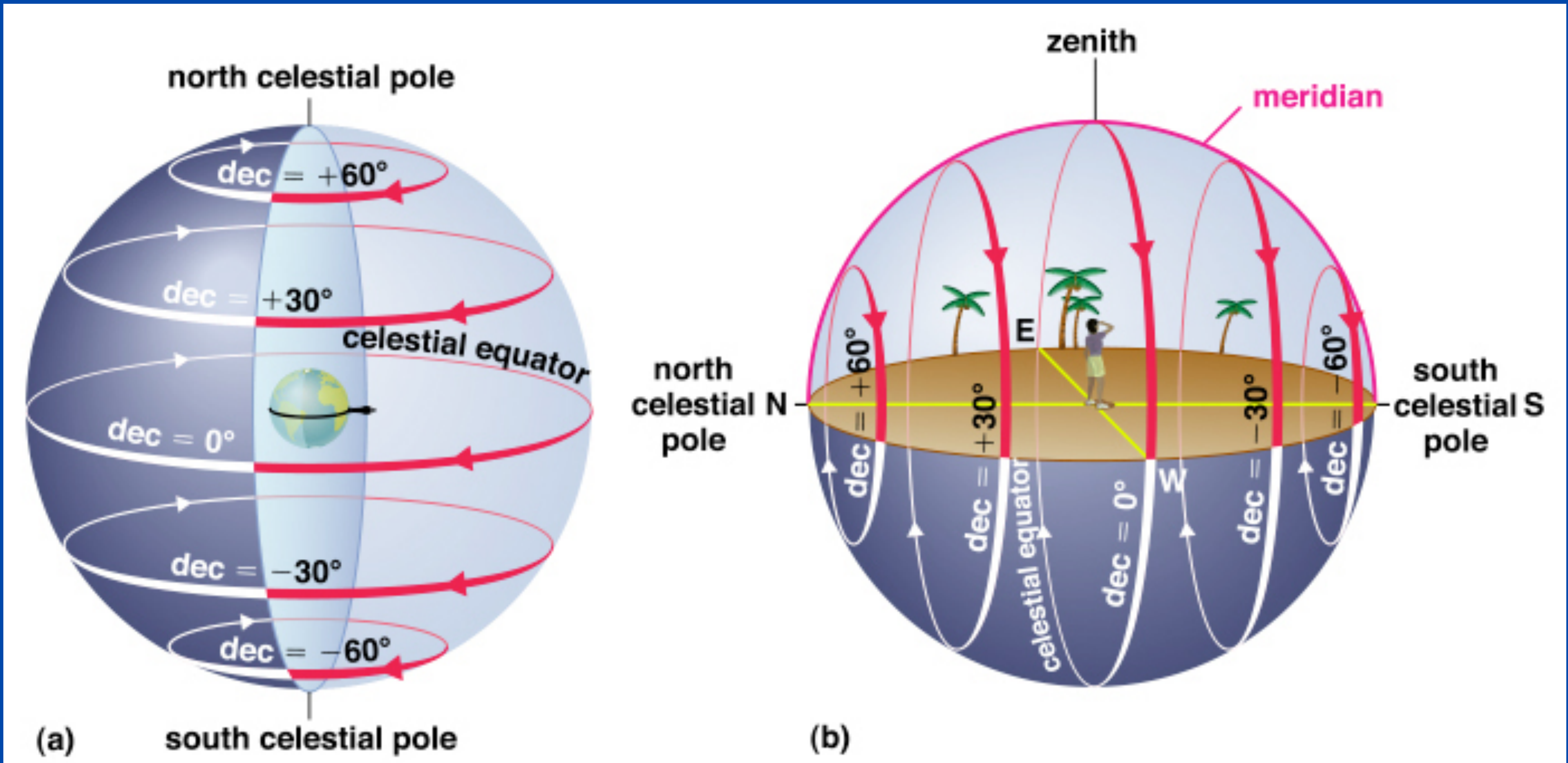
A constellation is a *region* of the sky.

In our Western Civilization, 88 constellations fill the entire sky.

Different cultures have invented different constellations for themselves.

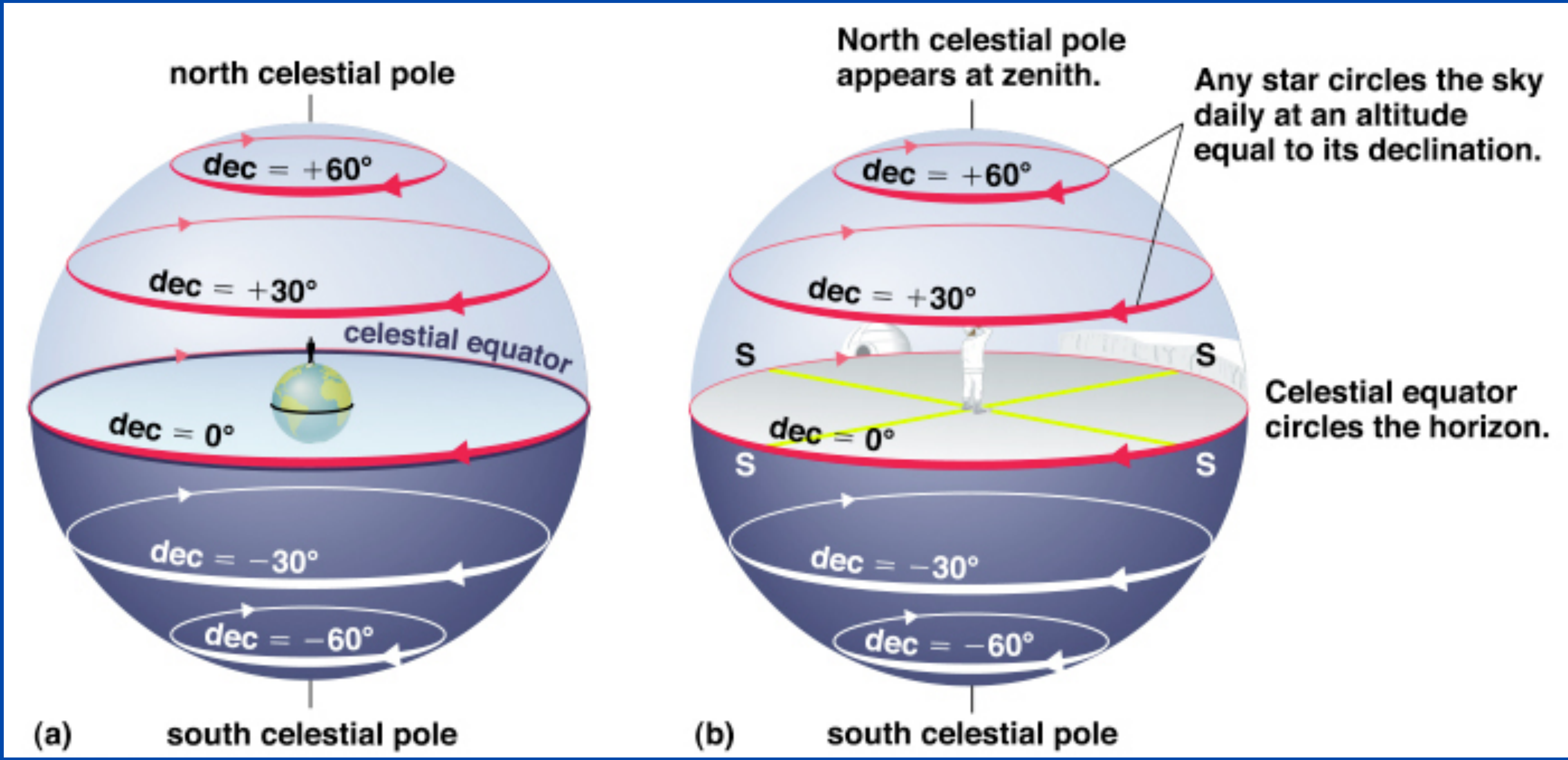


Nightly motion of stars is straight up and down if you are at the equator

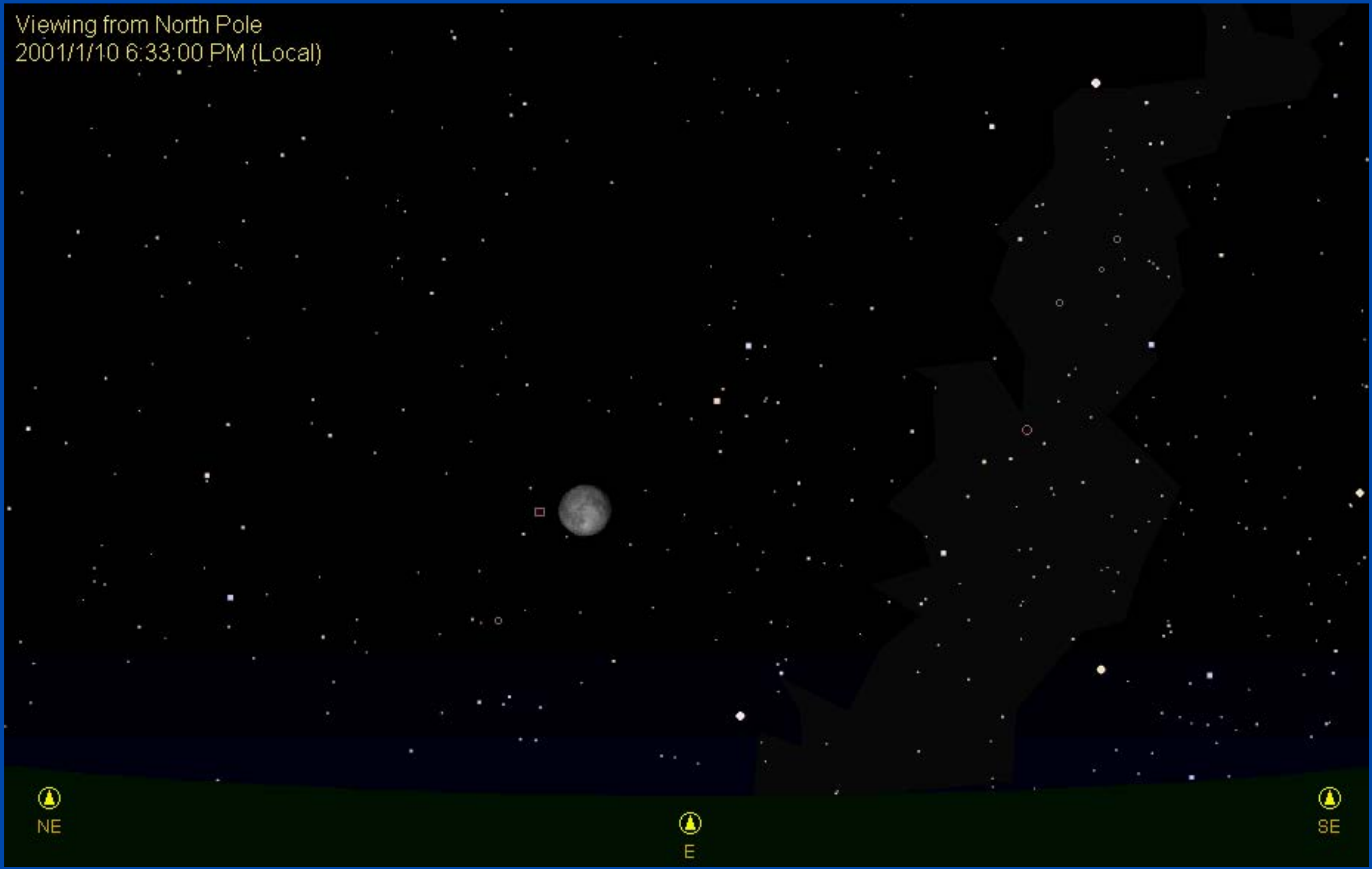


Nightly motion of stars is straight up and down if you are at the equator

Nightly motion of stars is horizontal if you are at the North Pole

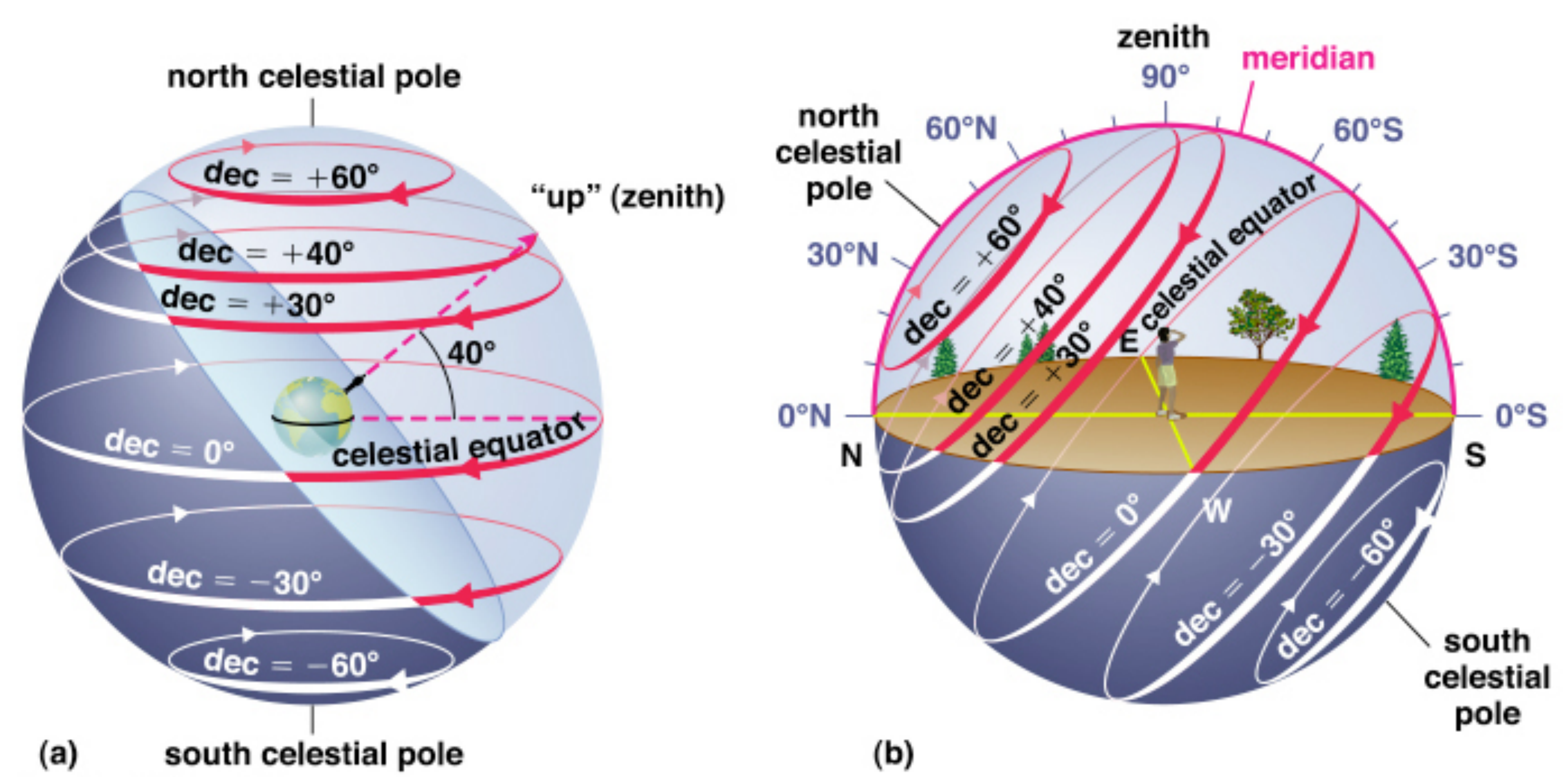


Nightly motion of stars is horizontal if you are at the North Pole



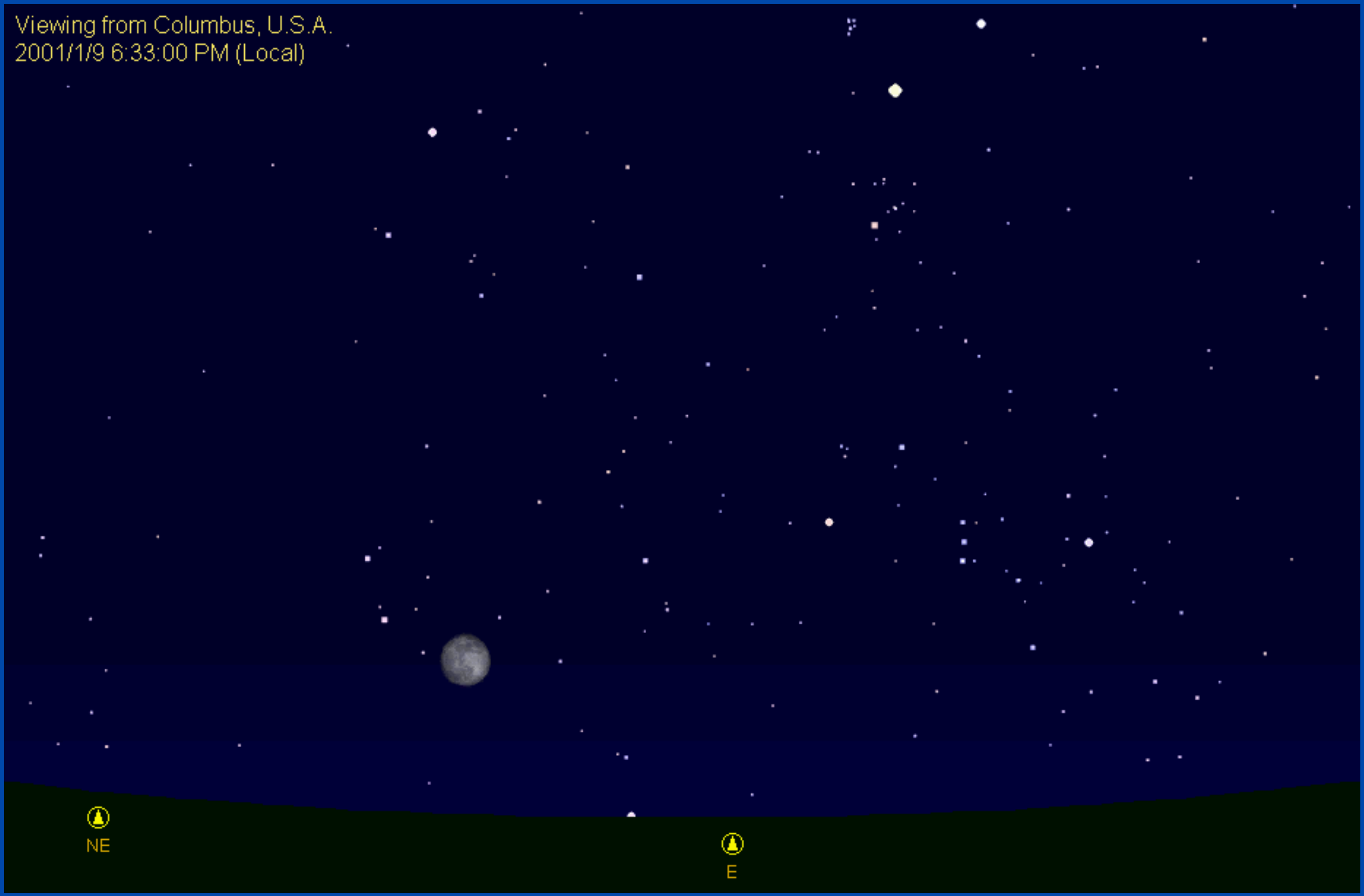
© Richard Pogge, Ohio State University.

Nightly motion of stars if you are at latitude 40 deg North

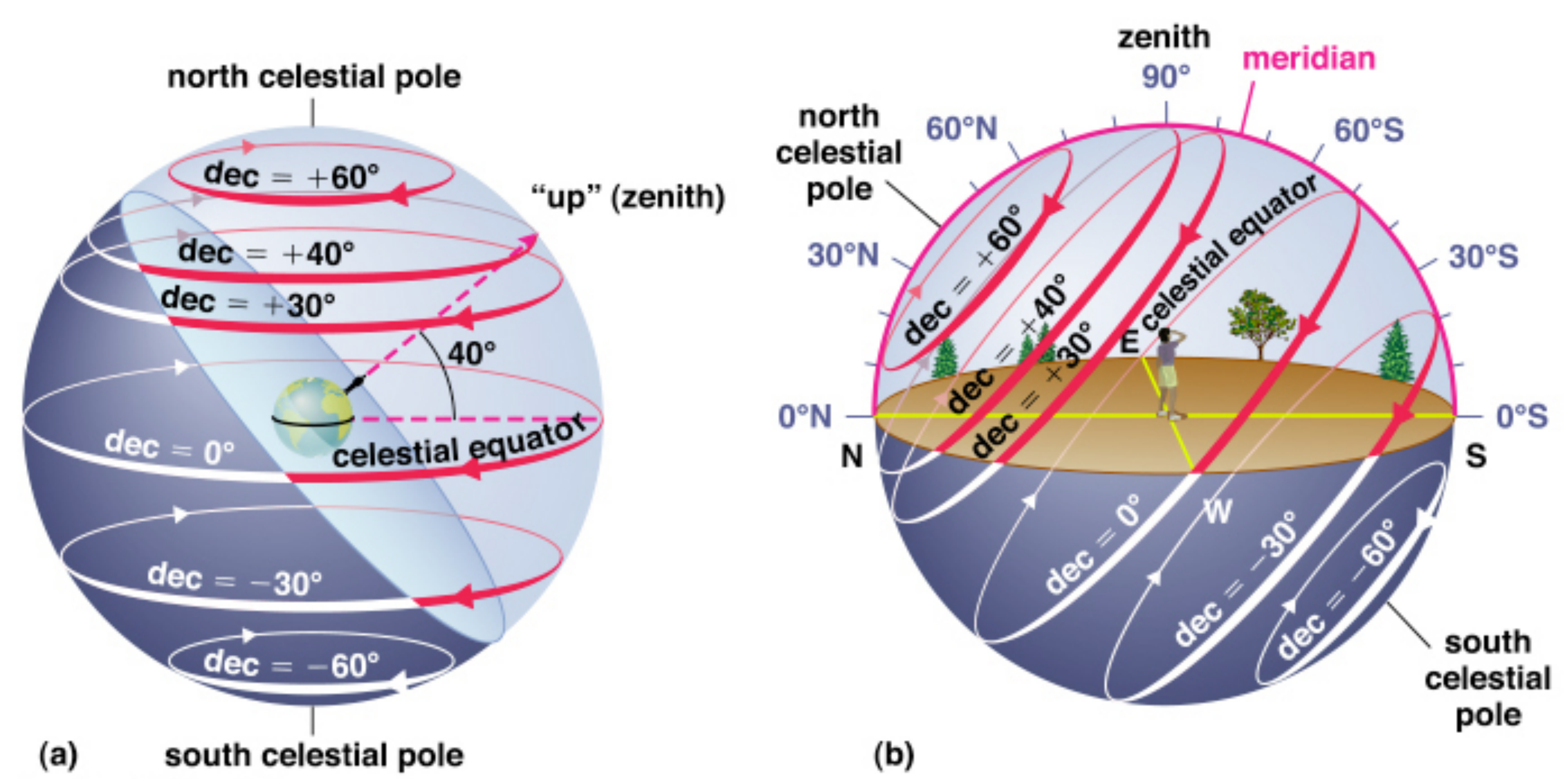


- Note: Latitude of Santa Cruz is 36.974 North

Nightly motion of stars at lat 40 deg North, looking to East



Nightly motion of stars at latitude 40 deg North, looking to North



Nightly motion of stars at latitude 40 deg North, looking to North

Where are we?

The Cosmic Distance Scale

- What is a light-year?
  First discuss speed of light.
- Light doesn't travel infinitely fast.
- If light propagates in a vacuum (as in outer space), its speed is a very specific number:

  $c = 300{,}000 \text{ km/sec} = 3 \times 10^{10} \text{ cm/sec}$

- At this speed, light would circle the Earth eight times in 1 second

Since speed of light is constant, can use it to measure distance

- distance = speed x time
- Use "dimensional analysis":
  - Write down units of each quantity in an equation
  - Then cross out places where the same unit is in a numerator and denominator
- Example:

$$L(km) = c\left(\frac{km}{\sec}\right) \times t(\sec)$$

Since speed of light is constant, can use it to measure distance

- distance = speed x time
- Use "dimensional analysis":
  - Write down units of each quantity in an equation
  - Then cross out places where the same unit is in a numerator and denominator
- Example:

$$L(km) = c\left(\frac{km}{\cancel{\sec}}\right) \times t(\cancel{\sec})$$

Define a light-year

- A light-year is the distance that light travels in one Earth-year
- How big is it?

$$1 \text{ light-year} = \text{speed of light} \times 1 \text{ year}$$

$$= \left(\frac{300{,}000 \text{ km}}{\cancel{\text{sec}}}\right) \times \left[(1\cancel{\text{year}}) \times \left(\frac{365 \cancel{\text{days}}}{1 \cancel{\text{year}}}\right) \times \left(\frac{24 \cancel{\text{hrs}}}{1 \cancel{\text{day}}}\right) \times \left(\frac{60 \cancel{\text{min}}}{1 \cancel{\text{hr}}}\right) \times \left(\frac{60 \cancel{\text{sec}}}{1 \cancel{\text{min}}}\right)\right]$$

$$= 9.46 \text{ trillion km}$$

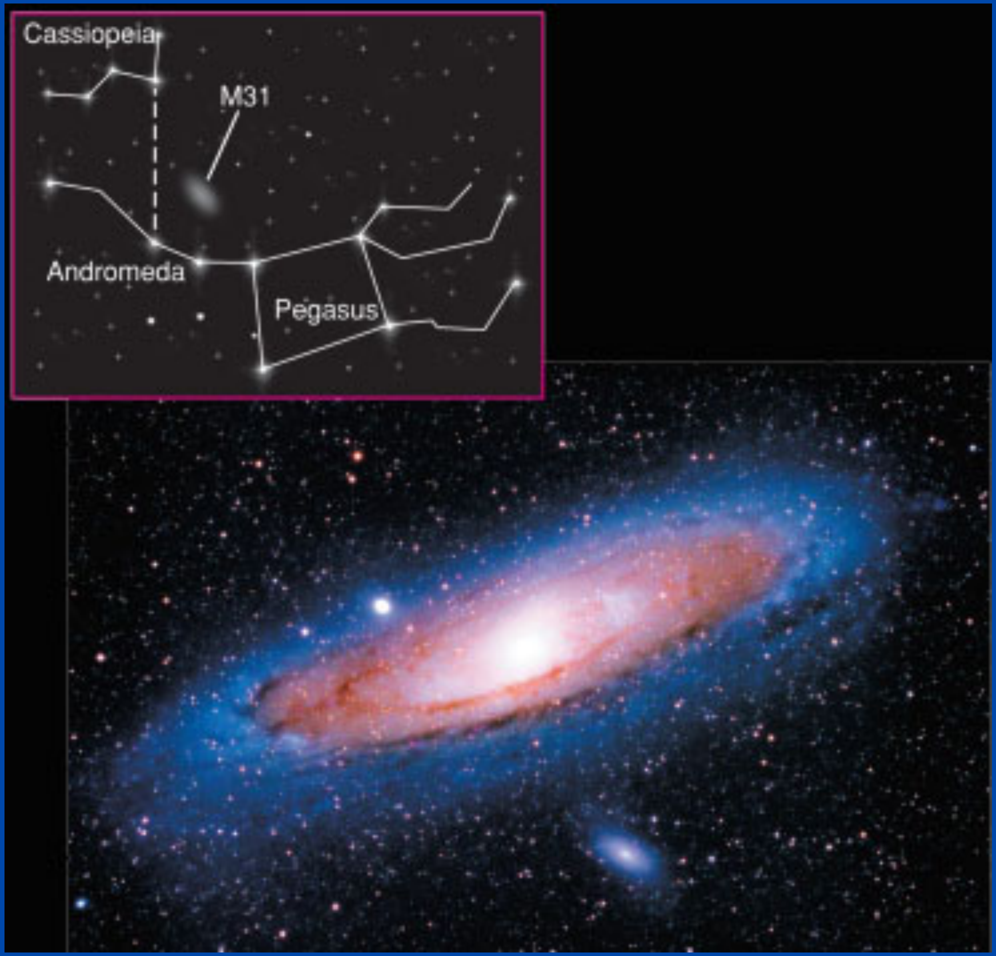
$$= 9.46 \times 10^{12} \text{ km}$$

Some examples of light travel-time

- **The Moon:**
  - It takes light 1 sec to travel from the moon to the Earth, so the Moon 1 light-sec away
- **The Sun:**
  - It takes light 8 minutes to travel from the Sun to the Earth, so the Sun is 8 light-minutes away
- **The nearest star, Proxima Centauri:**
  - It takes light about 4 years to travel from Proxima Centauri to the Earth, so this star is 4 light-years away

Example:

- This photo shows the Andromeda Galaxy as it looked about 2 1/2 million years ago.
- Question: When will we be able to see what it looks like now?



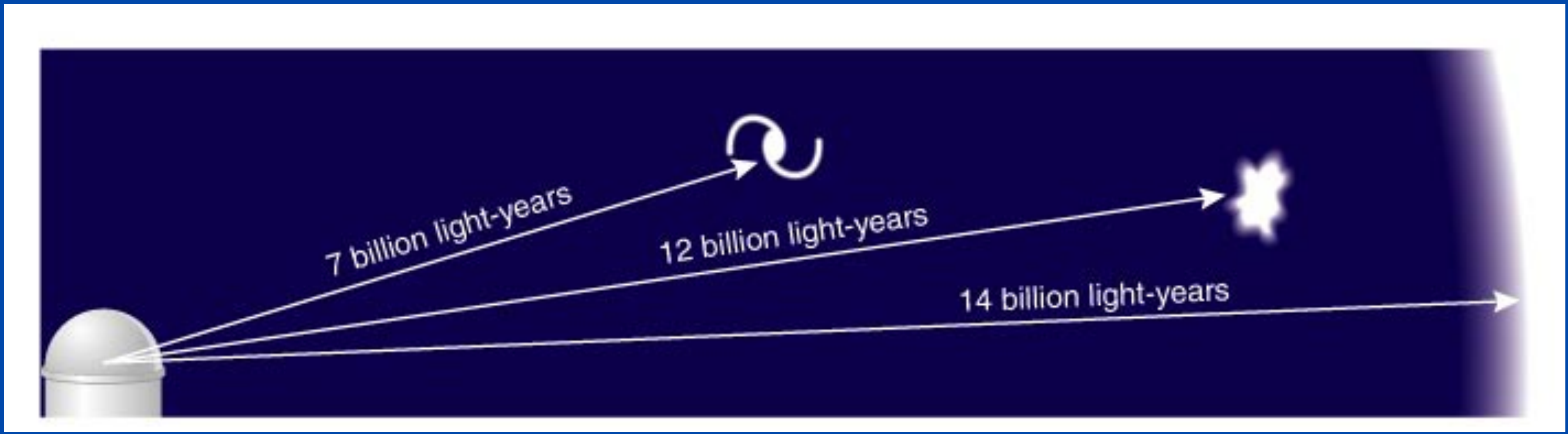
Implications of the finite speed of light

- Because it takes light a finite amount of time to reach us,

  the farther away we look in distance, the further back we look in time

- In 1987 when we saw a supernova explosion in the Large Magellanic Cloud (a neighboring galaxy150,000 light-years away), the supernova had actually exploded 150,000 years ago
- When we look at galaxies that are more and more distant from us, we are seeing them at younger and younger stages of their evolution

At great distances, we see objects as they were when the universe was much younger



ConcepTest

If the speed of light were half what it is now, then a “light-year” would

a) take half as long to traverse at light speed

b) take the same amount of time to traverse at light speed

c) last twice as many months

d) last half as many months

ConcepTest

If the speed of light were half what it is now, then a "light-year" would

a) take half as long to traverse at light speed

b) take the same amount of time to traverse at light speed

c) last twice as many months

d) last half as many months

The expansion of the universe and the Big Bang

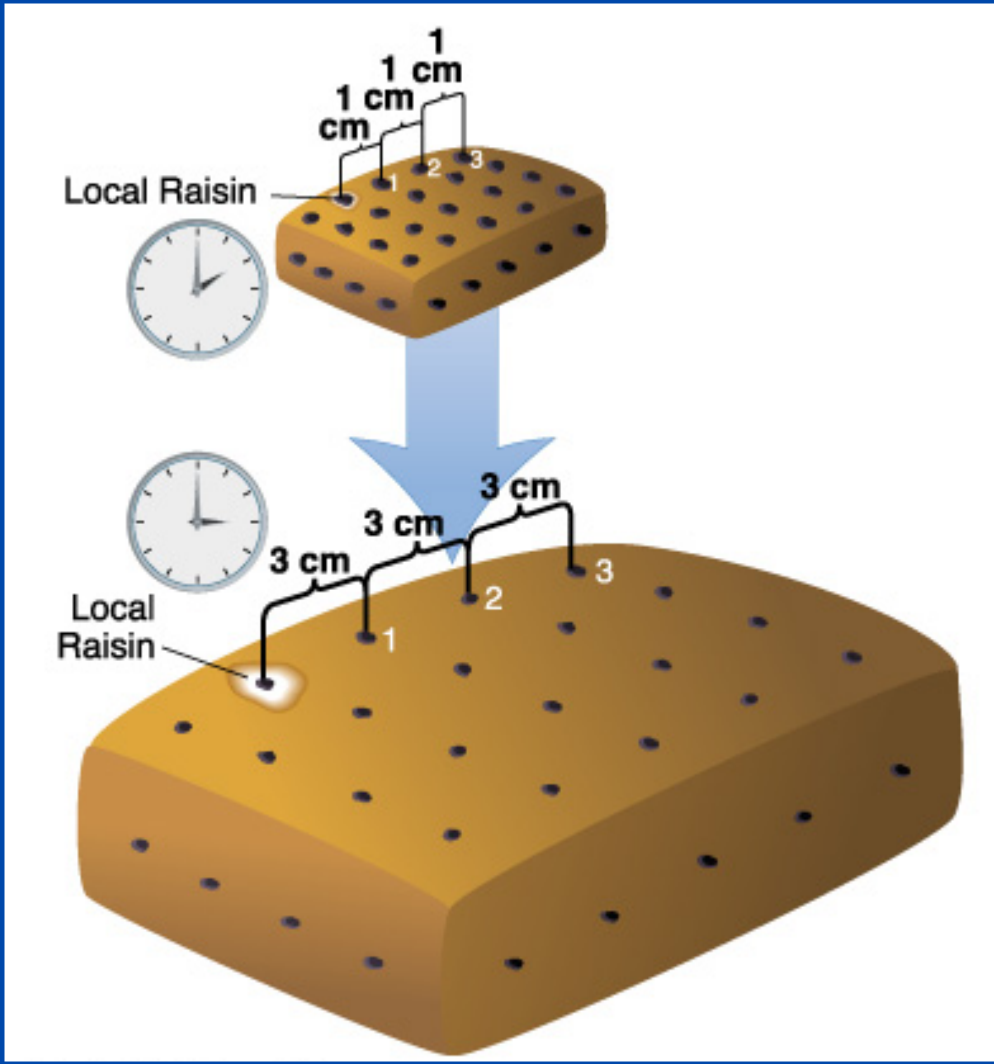
- **Observation:**
  - **Virtually every galaxy outside our Local Group is moving away from us**
  - **The farther away a galaxy is, the faster it is moving away from us**
  - **How is the observation made? From Doppler shift of spectral lines (will discuss in later lecture).**
    - **» Color of light becomes redder if the object emitting the light is moving away from us.**

- **Recession velocities are large:**
  - **tens of thousands to 100's of thousands of km/sec**

What's going on?

- Entire universe is expanding
  – (It's not that everybody hates us....)
- Furthermore, at every place in the universe, it looks like the rest of the galaxies are all receding, and more distant galaxies are receding faster
- Analogies to help understand this:
  – A jungle gym that whose bars are all getting longer
  – A sponge cake that is expanding as it bakes

"Local Sponge Cake" Example



- Every raisin sees all the other raisins moving away from it
- More distant raisins move away faster

Click here

The Big Bang

- This is as far back as we can hope to measure
- Every place in the universe was (almost) infinitely dense and infinitely hot
- Ever since the Big Bang, the universe has been expanding, becoming less dense (on the average), and cooling off

ConcepTest

There must be some very large distance such that light from a galaxy at that distance hasn't yet reached us during the age of the universe. The expansion velocity of galaxies at that distance, relative to us, must be

a) zero

b) infinite

c) less than the speed of light

d) the speed of light or greater

ConcepTest

There must be some very large distance such that light from a galaxy at that distance hasn't yet reached us during the age of the universe. The expansion velocity of galaxies at that distance, relative to us, must be

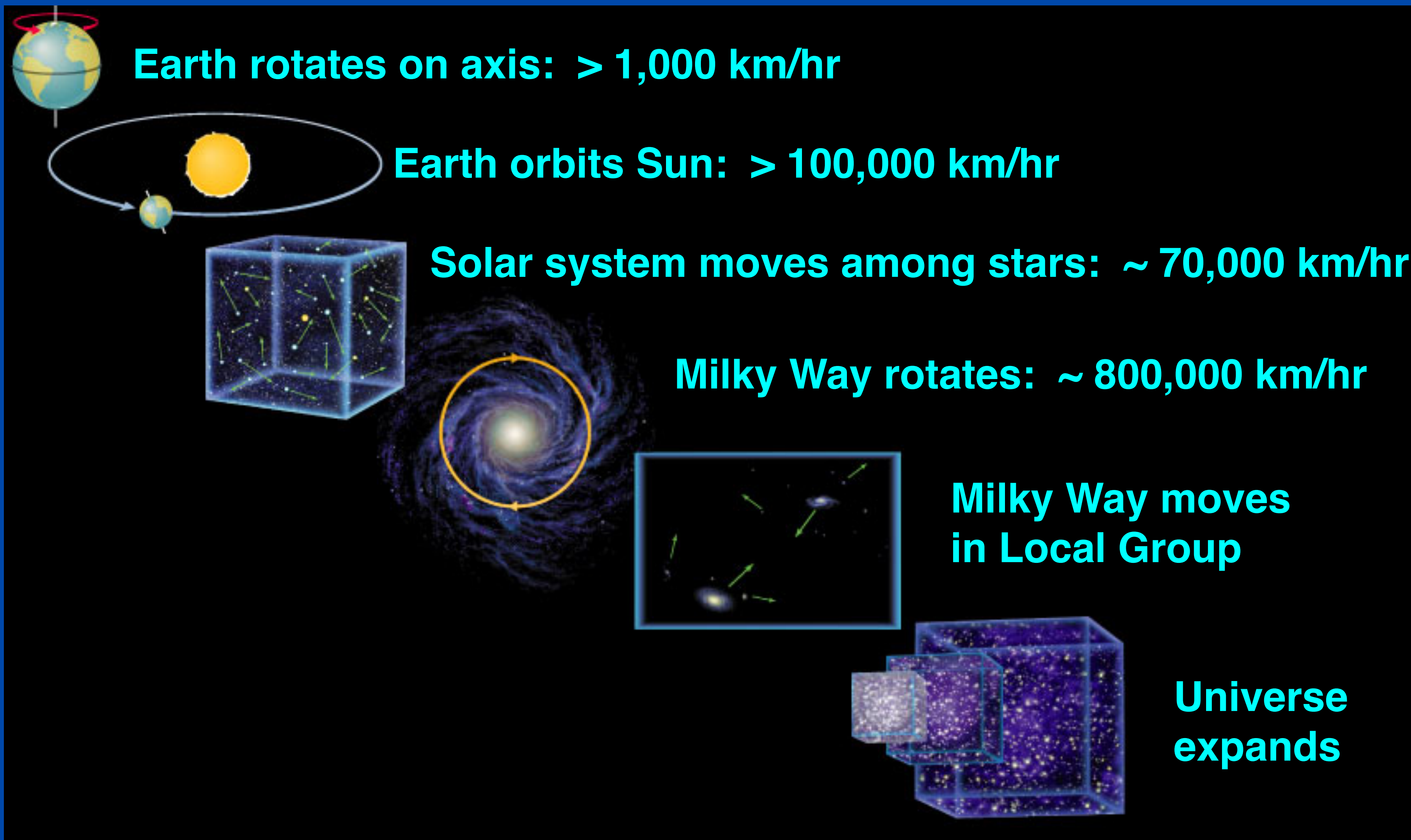
a) zero

b) infinite

c) less than the speed of light

d) the speed of light or greater

The Universe in motion...



Review

- How can we know that the universe was like in the past?
  - When we look to great distances we are seeing events that happened long ago because light travels at a finite speed
- Can we see the entire universe?
  - No, the observable portion of the universe is about 14 billion light-years in radius because the universe is about 14 billion years old

Our Celestial Address

Physical Sciences Building

UCSC

City of Santa Cruz

California

USA

The Earth

The Solar System

The Milky Way Galaxy

The Local Group of Galaxies

The Local Supercluster of Galaxies

The Universe

Dark matter and dark energy: Unseen influences on the universe

Dark Matter: **An undetected form of mass that emits little or no light, but whose existence we infer from its gravitational influence**

Dark Energy: **An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate**

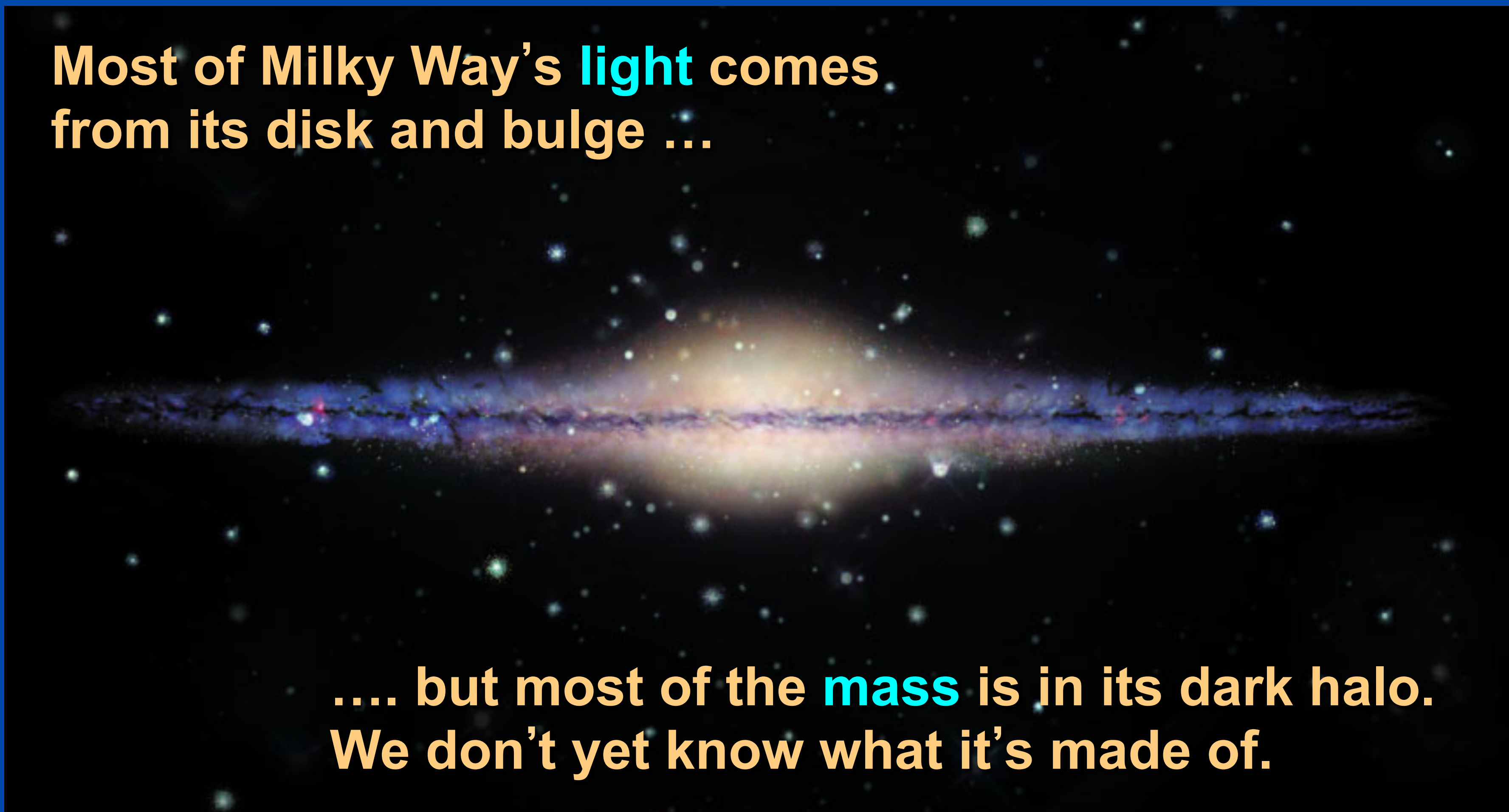
The surprising contents of the Universe

- **Ordinary matter ~ 4.4%**
- **Dark matter ~ 23%**
- **Dark energy ~ 73%**

  (assumes energy = mass x c^2)

All the atoms and molecules we are familiar with are <5% of the mass of the universe (!)

Detailed study of Milky Way's rotation reveals presence of "Dark Matter"

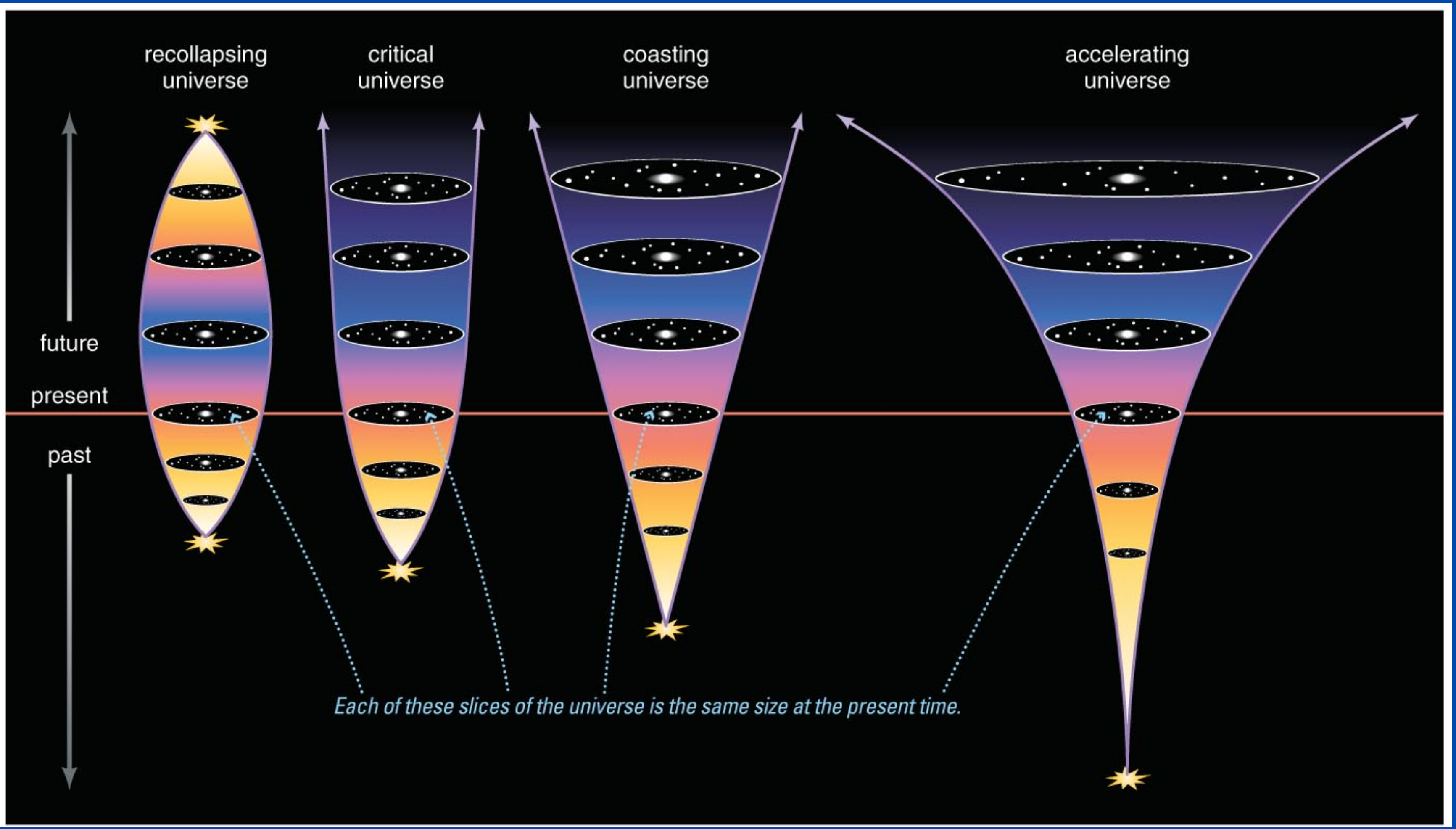


Measuring dark matter in clusters of galaxies

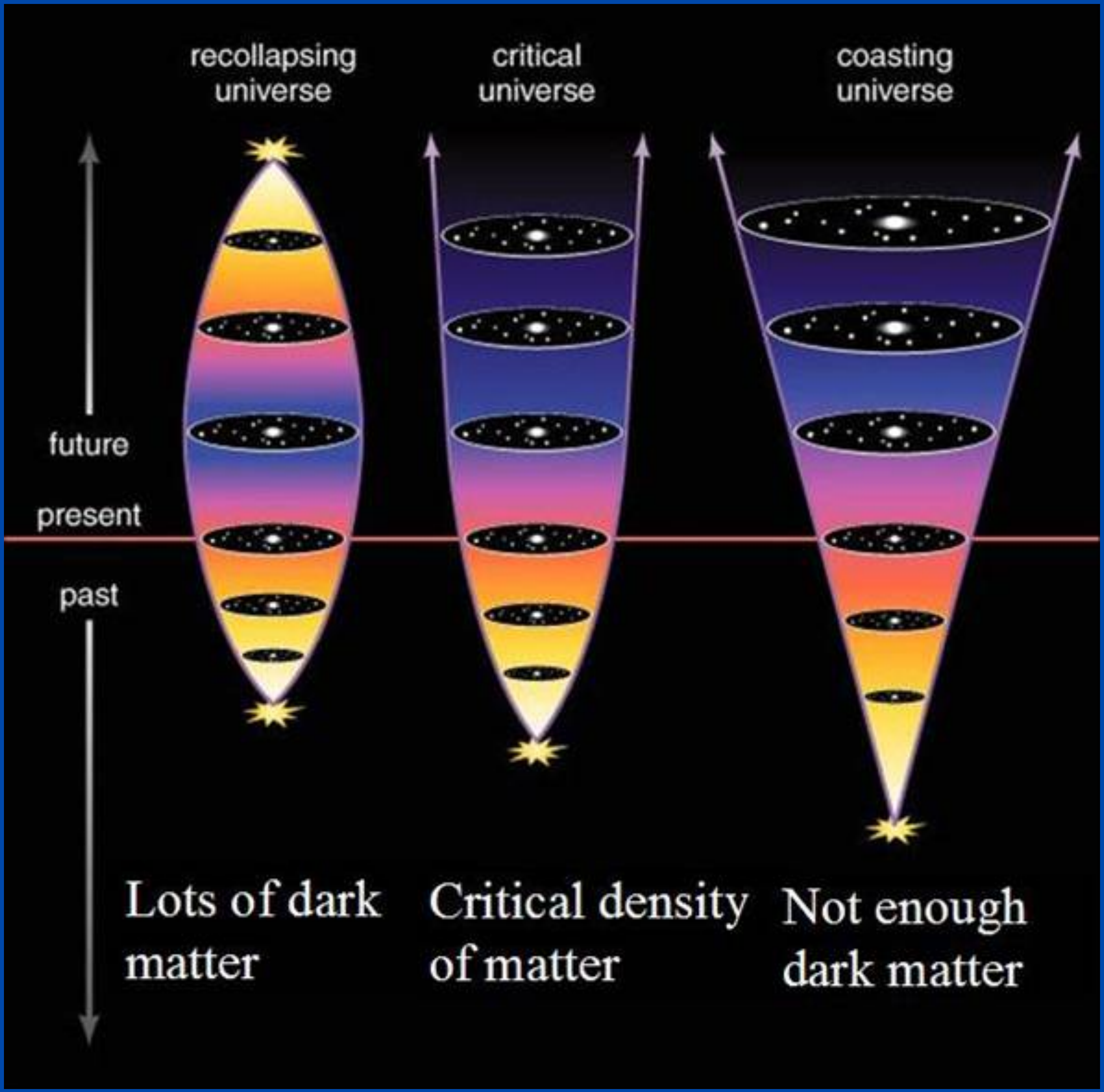
- Galaxy clusters contain large amounts of X ray-emitting hot gas.
- Temperature of hot gas (particle motions) tells us cluster mass:

85% dark matter
13% hot gas
2% stars

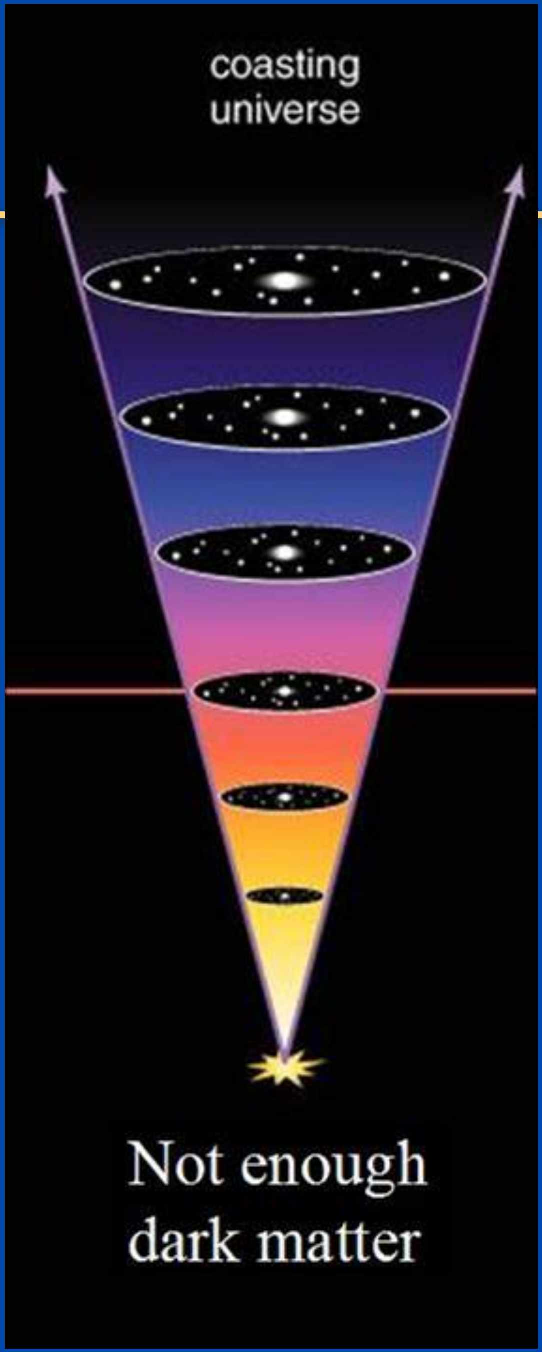
Will the universe continue expanding forever?



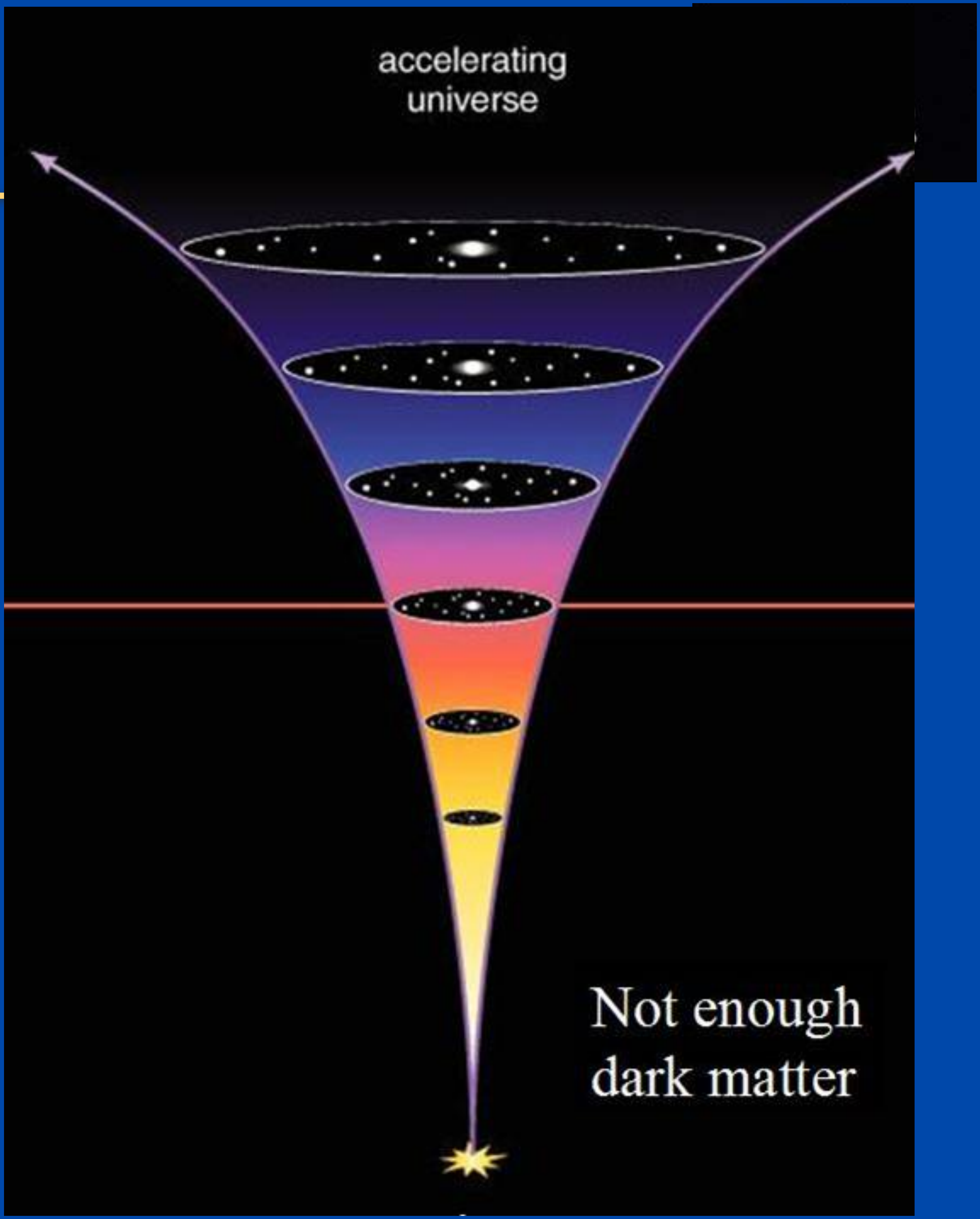
The fate of the universe depends on the amount of dark matter

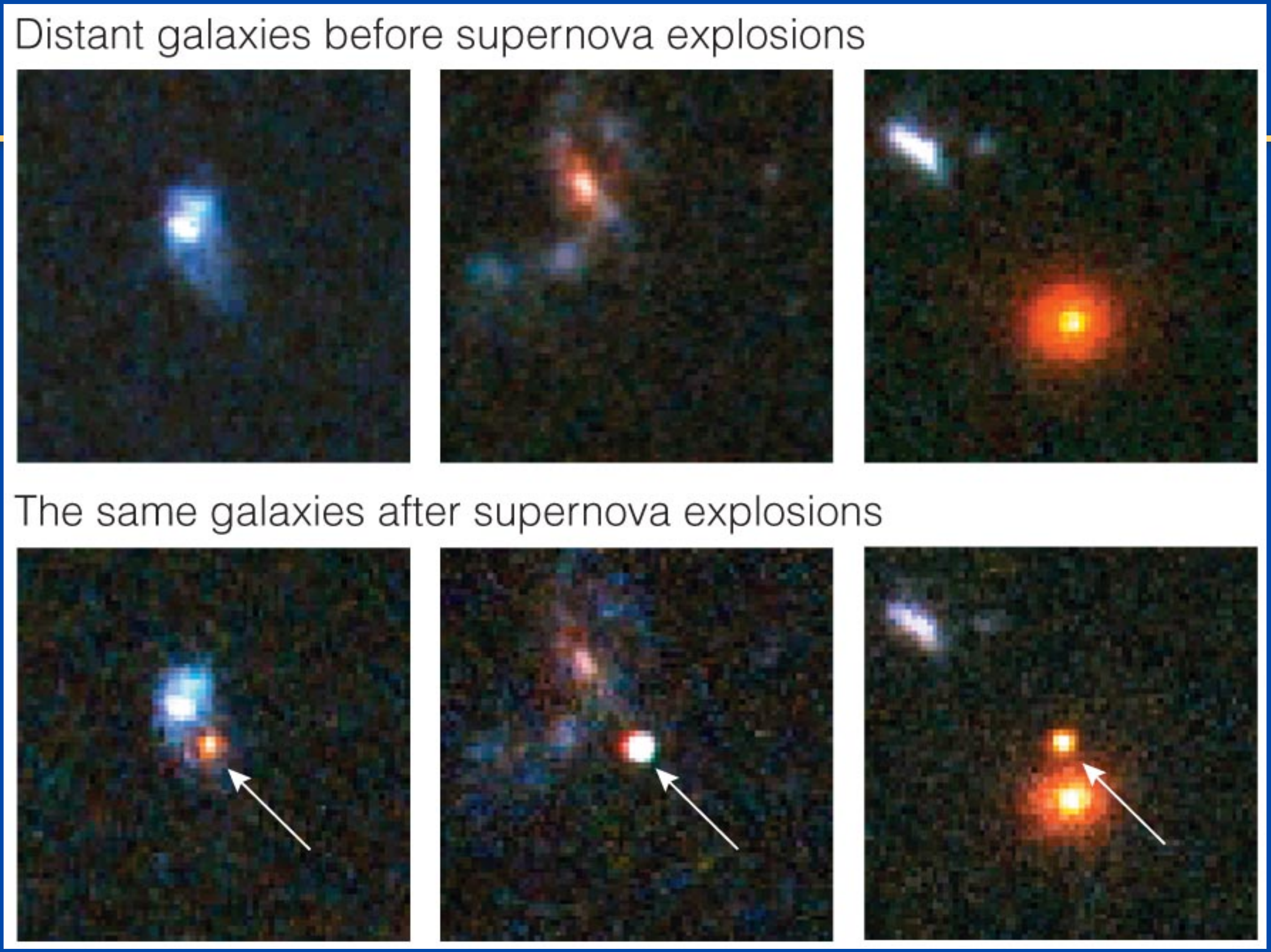


- *The amount of dark matter is ~25% of the critical density*
- *Hence we expect the expansion of the universe to overcome its gravitational pull*



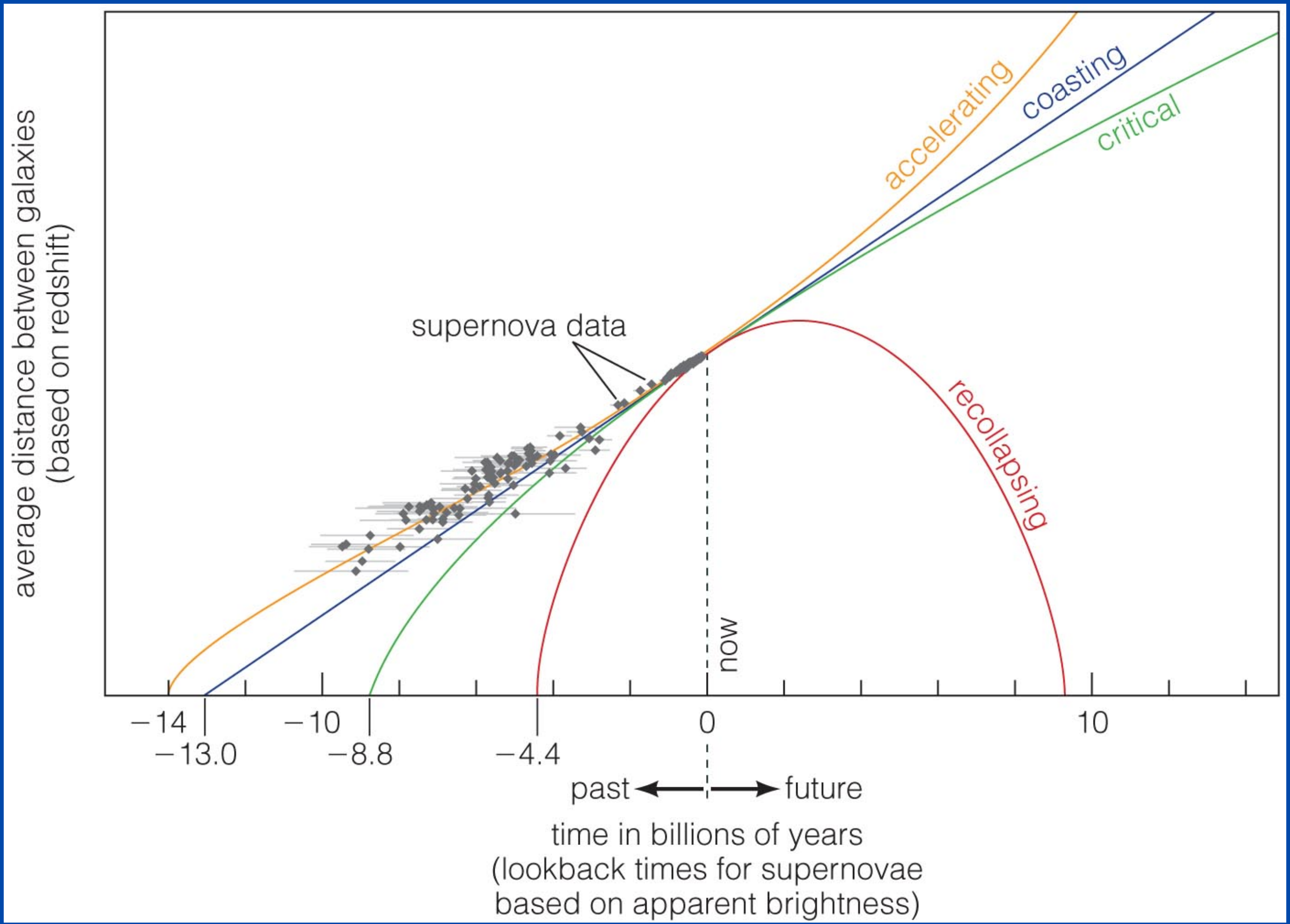
- *In fact, the expansion appears to be speeding up!*
- *Dark Energy?*





Brightness of distant supernovae tells how much the universe has expanded since they exploded

An accelerating universe best fits the supernova data



Supports the Dark Energy hypothesis

Review: Dark Matter and Dark Energy

- **Dark Matter:**
  - Exerts gravitational pull on all scales
  - Many lines of evidence
  - Has not yet been directly detected

- **Dark Energy:**
  - Main action is on largest physical scales
  - Several lines of evidence, including accelerating expansion of universe

All the atoms and molecules we are familiar with are <5% of the mass of the universe (!)

Reading assignments and next few lectures

- Tuesday April 8th:
  - Reading assignment: Chapters 3 and 4 in Bennett
  - Lecture will cover Chapter 3 + 1st part of Chapter 4
- Thursday April 10th: NO LECTURE
- Tuesday April 15th
  - Supplementary optional reading assignment with some calculus (I will post on the class website)
  - Lecture will cover remainder of Chapter 4

Homework assignment (problem set)

- **Due Tuesday April 15th**
- **I will post the assignment on the class website,**

  http://www.ucolick.org/~max/Astro18-2014/Astro18.html