Announcements

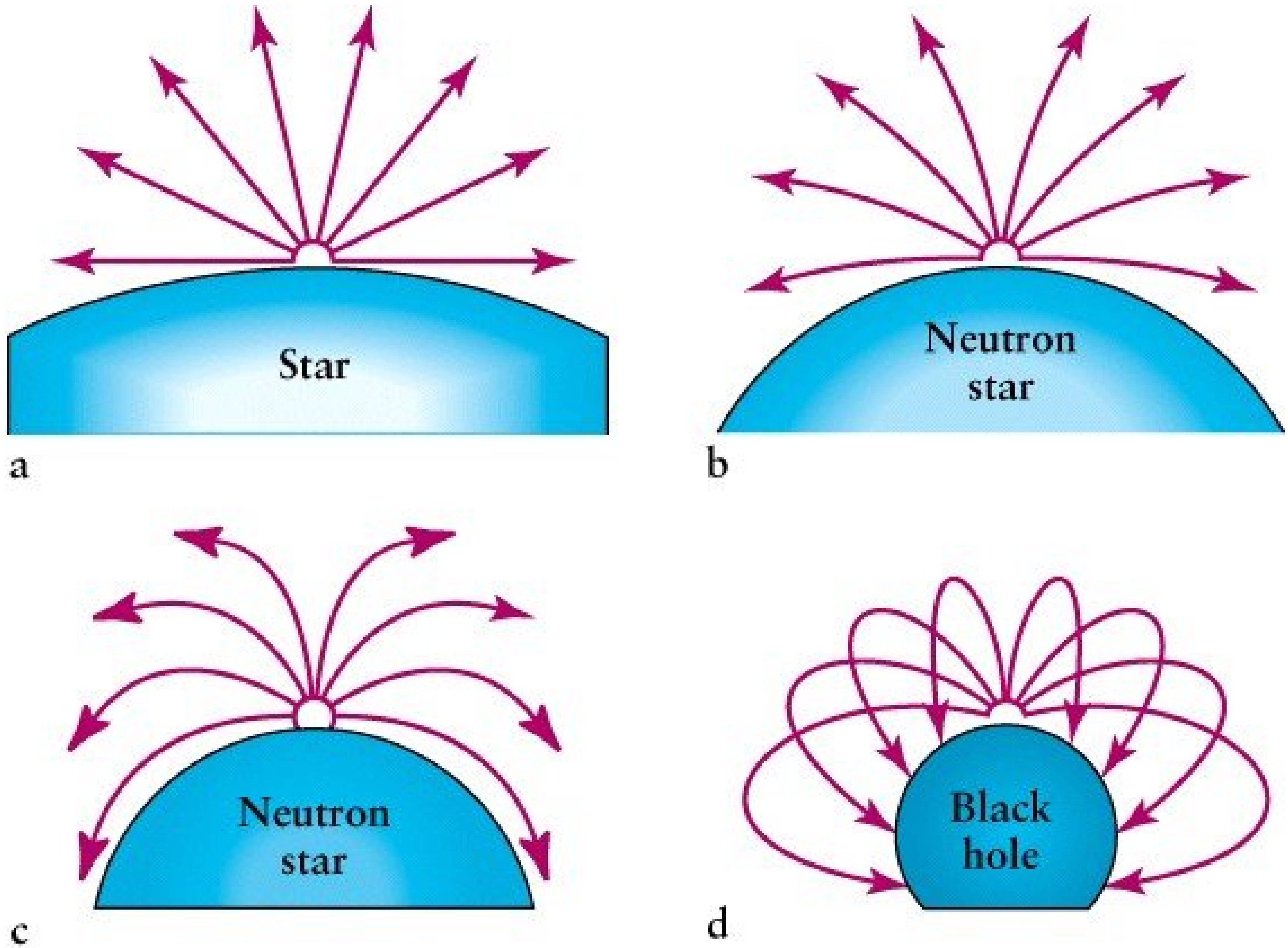
- Today: Review for Midterm #3
- Monday: Midterm #3
  - same rules as Midterms 1 & 2
  - 50 questions, including 5 bonus questions
  - no books, notes, calculators
- Next Wednesday & Friday: NO CLASS :)

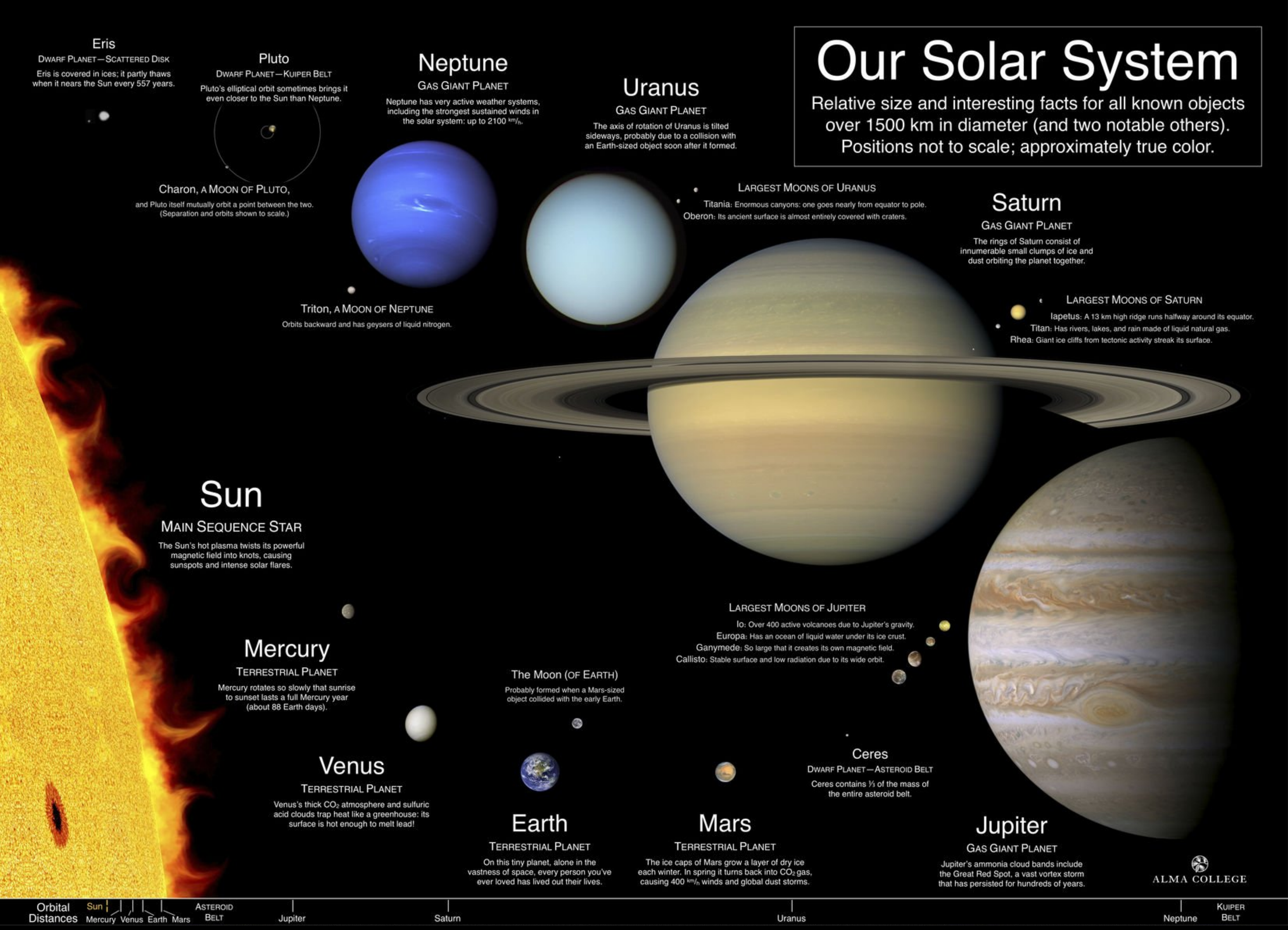
Neutron Star Fun Facts

- R≈15 km and M≈1.5 MSun
- Central density 2-10 times that of atomic nucleus
  - 1 teaspoon is about 10^{12} kg
  - a cube 300 meters on a side has the same mass as the Earth
- Magnetic field >10^{12} times that on Earth
  - erase credit cards from 30,000 km & kill from 200 km
- Spin frequencies from 0.1 Hz to 716 Hz → pulsars
  - faster than a kitchen blender!

Black holes and an upper limit on the mass of neutron stars

- The pressure from nuclear forces in a neutron star keep the star from collapsing.
- But there is a maximum pressure that nuclear forces can exert and beyond 3 times the mass of the Sun, gravity must win.
- At this point, the neutron star will collapse to a black hole, an object whose gravity is so strong that not even light can escape.
- Nothing can escape from a black hole.
- Only the most massive stars (O-type stars) end their lifes as black holes!


Star
a
Neutron
star
b
Neutron
star
c
Black
hole
d



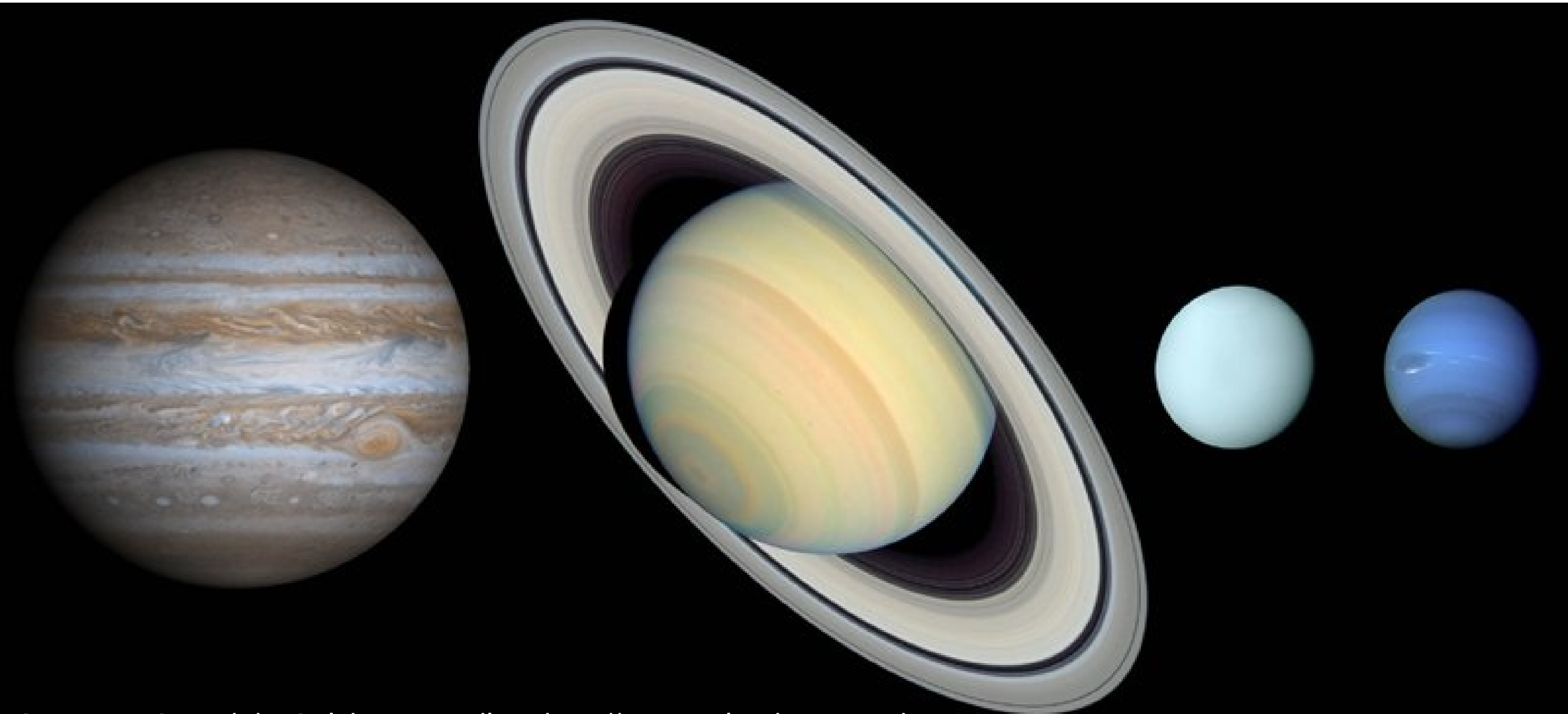
Source: http://www.slimy.com/~steuard/teaching/solarsystem/

Terrestrial Planets

- Close to the Sun
- Made of rocks (silicon) and iron
- High density
- Small (~10000 km in diameter)

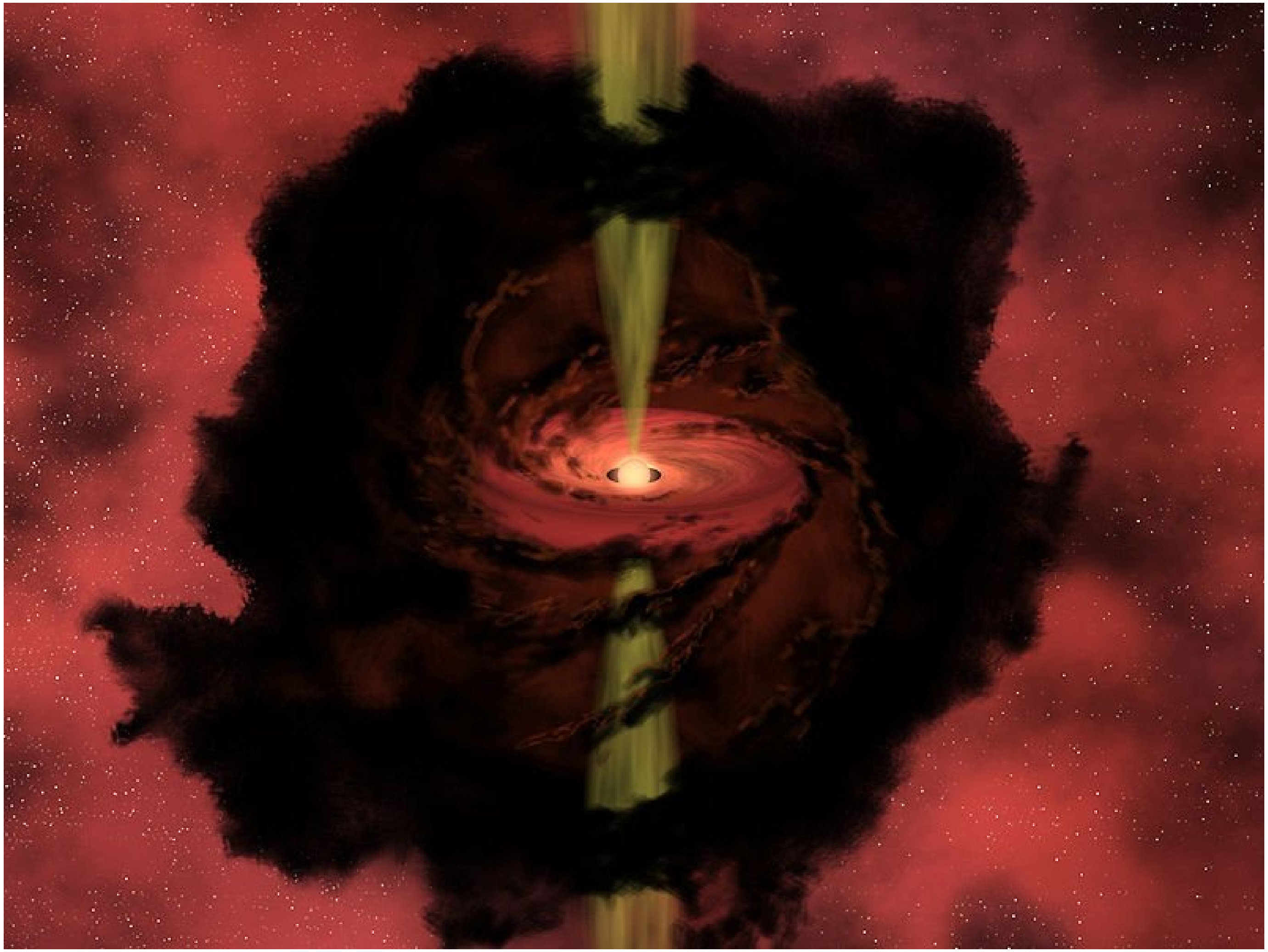
Jovian Planets

- Farther from the Sun
- Made of gases (hydrogen, helium, methane, water, ammonia)
- lower density
- large (~100,000 km in diameter)



Source & Copyright Calvin J. Hamilton http://www.solarviews.com)

The protostar



The collapse of one of these clouds forms a **protostar** and the disk of gas that surrounds it

Condensation of the planets

- Gas does not condense (because it remains gas), but **dust** can gather – tiny chunks of rocky and icy matter, with sizes of about 10-5 m
- Dust grains form in cool atmospheres of old stars, are ejected, grow by accumulating molecules from interstellar gas
- Dust collects into larger bodies: dust bunnies!

Density of Planets

Density of a object is:

Density = mass / volume

Density of some common materials:

- Water ~ 1000 $kg/m^{3};$
- Rock ~ 2000-3000 kg/m^3
- Iron ~ 8000 kg/m^3

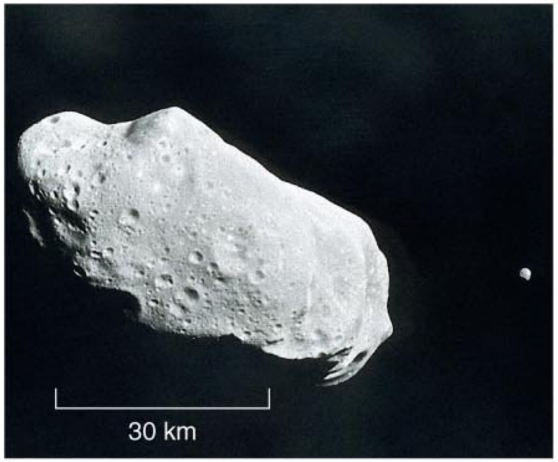
- For objects like the Sun, Jupiter, Saturn: density is ~ 1000 kg/m^3
- For terrestrial bodies like Earth, Mercury, Venus: density is around 5000 kg/m^3

Asteroids

- Rocky bodies that are held together by gravity and internal forces
- Most live in a belt between Mars and Jupiter at 2.8 A.U. called the asteroid belt
- about 100,000 rocky objects bigger than 1 km exist
- Ceres is the largest asteroid with a diameter of ~1000 km
- A few thousand have orbits that cross Earth's orbit – called near-Earth asteroids (NEAs)
- Some are near Jupiter (60 degrees ahead and behind) and are called Trojans

Asteroids and Meteoroids

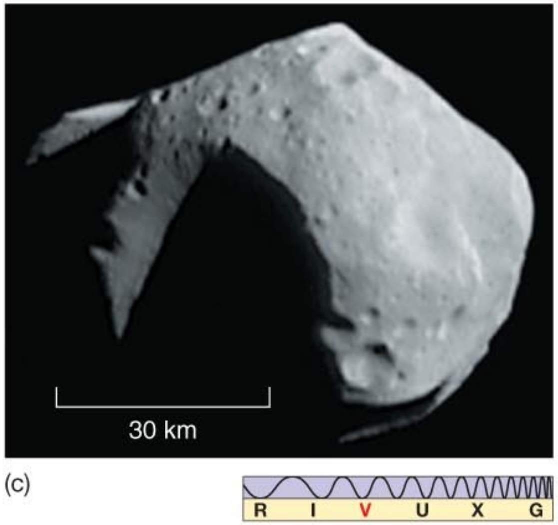
Asteroids and meteoroids have rocky composition; asteroids are bigger.



(b)

Asteroid Ida with its moon, Dactyl

Asteroid Mathilde



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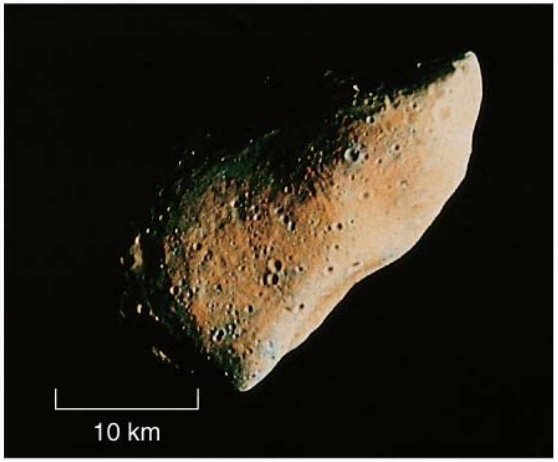


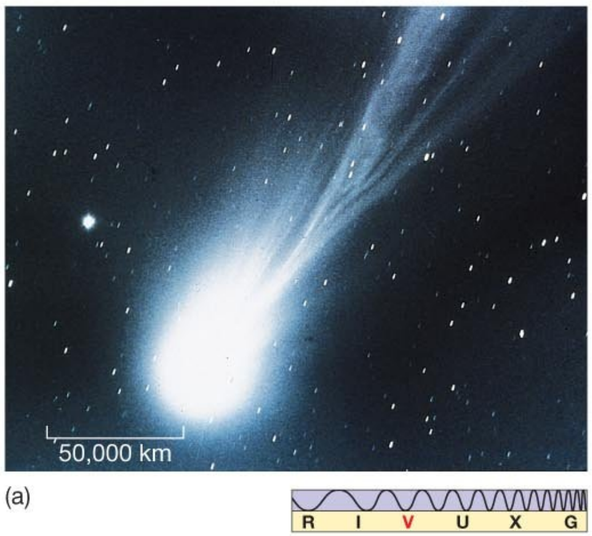
(a)

Asteroid Gaspra

Comets

Comets are icy, with some rocky parts.

The basic components of a comet



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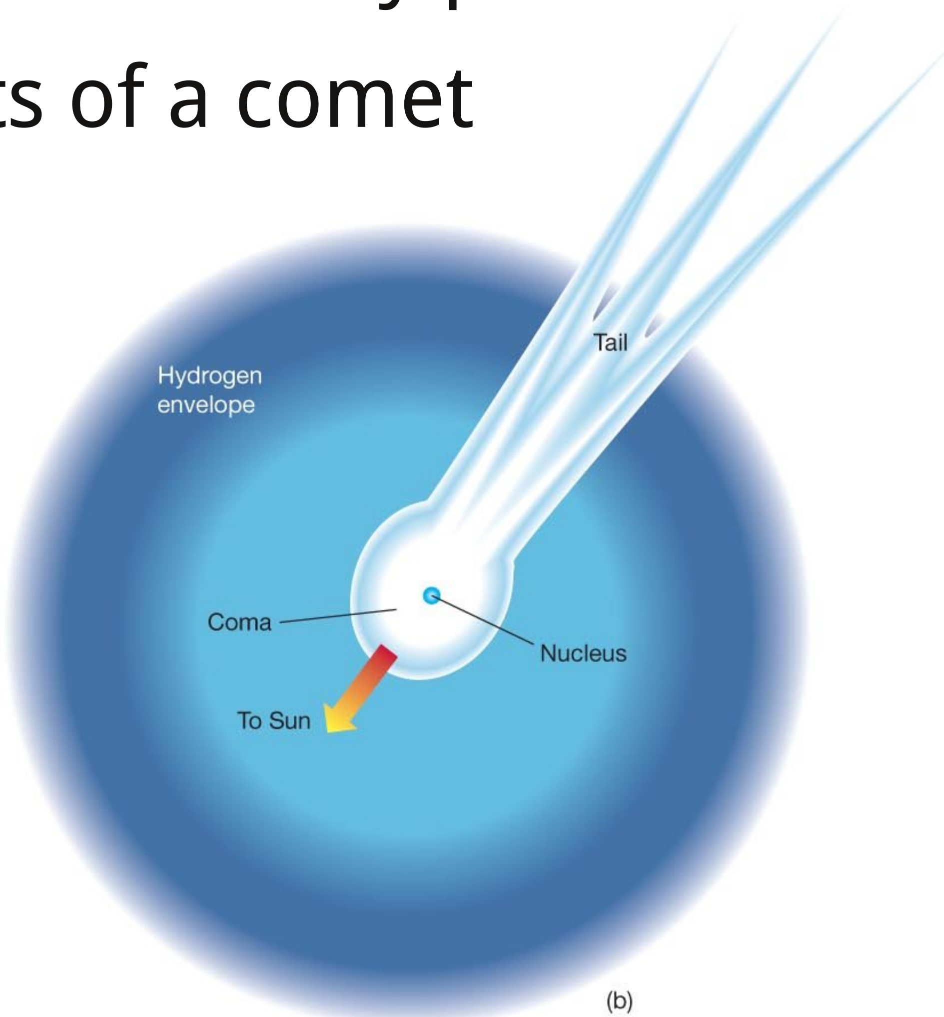
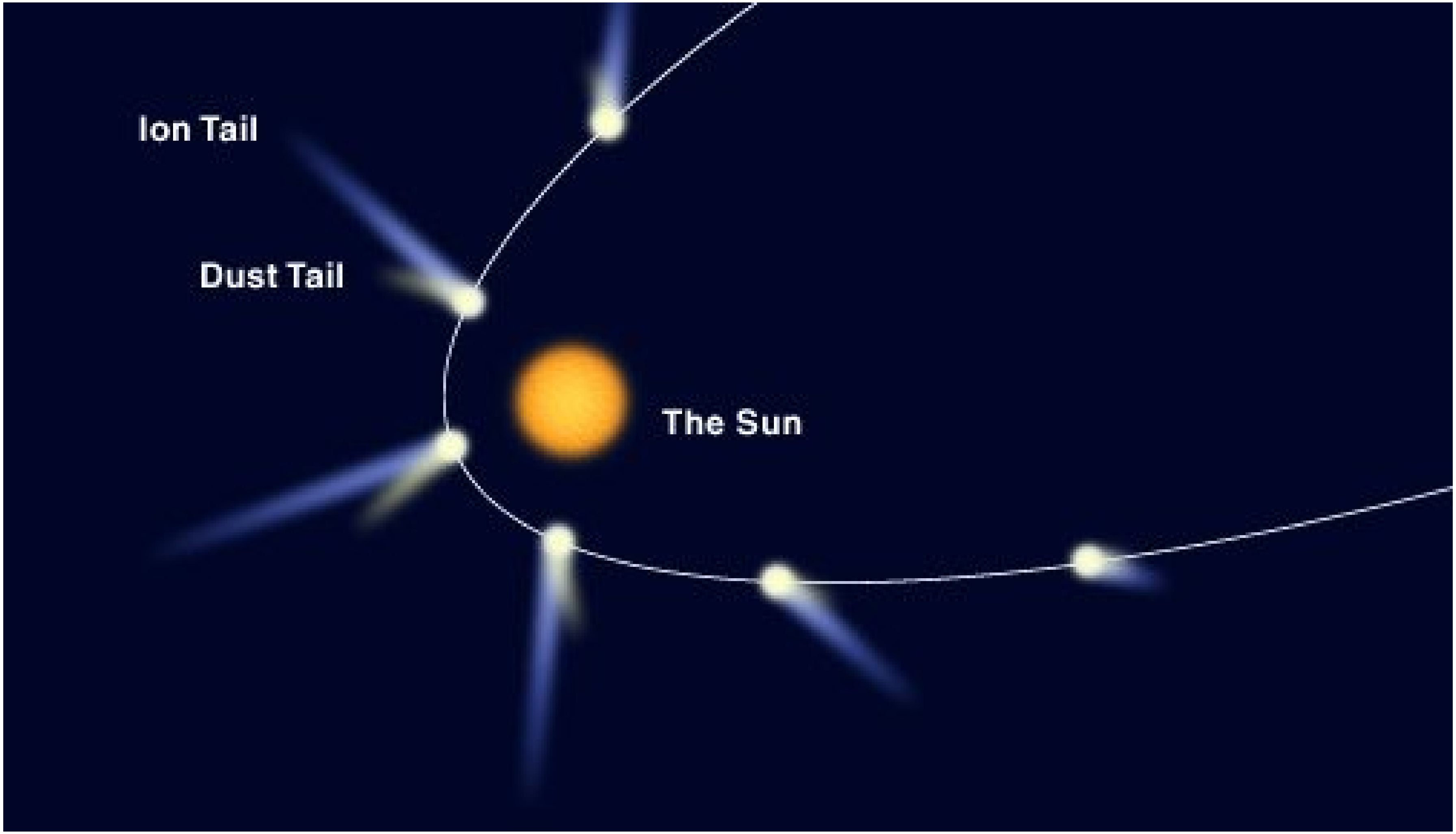


(b)

Asteroids, Meteroids, Meterorites

- Asteroids: Big rubble piles in space
- Asteroid enters Earth's atmosphere → becomes visible as meteoroid (most meteoroid are small, pebble-sized or smaller)
- Meteoroid is large enough to not burn up in the atmosphere and makes it to the ground → meteorite

Comet’s tail



Comet tails point away from the sun due to the solar wind and the light from the Sun.

Mercury

Radius ~ 2400 km

mass ~ 5% of Earth

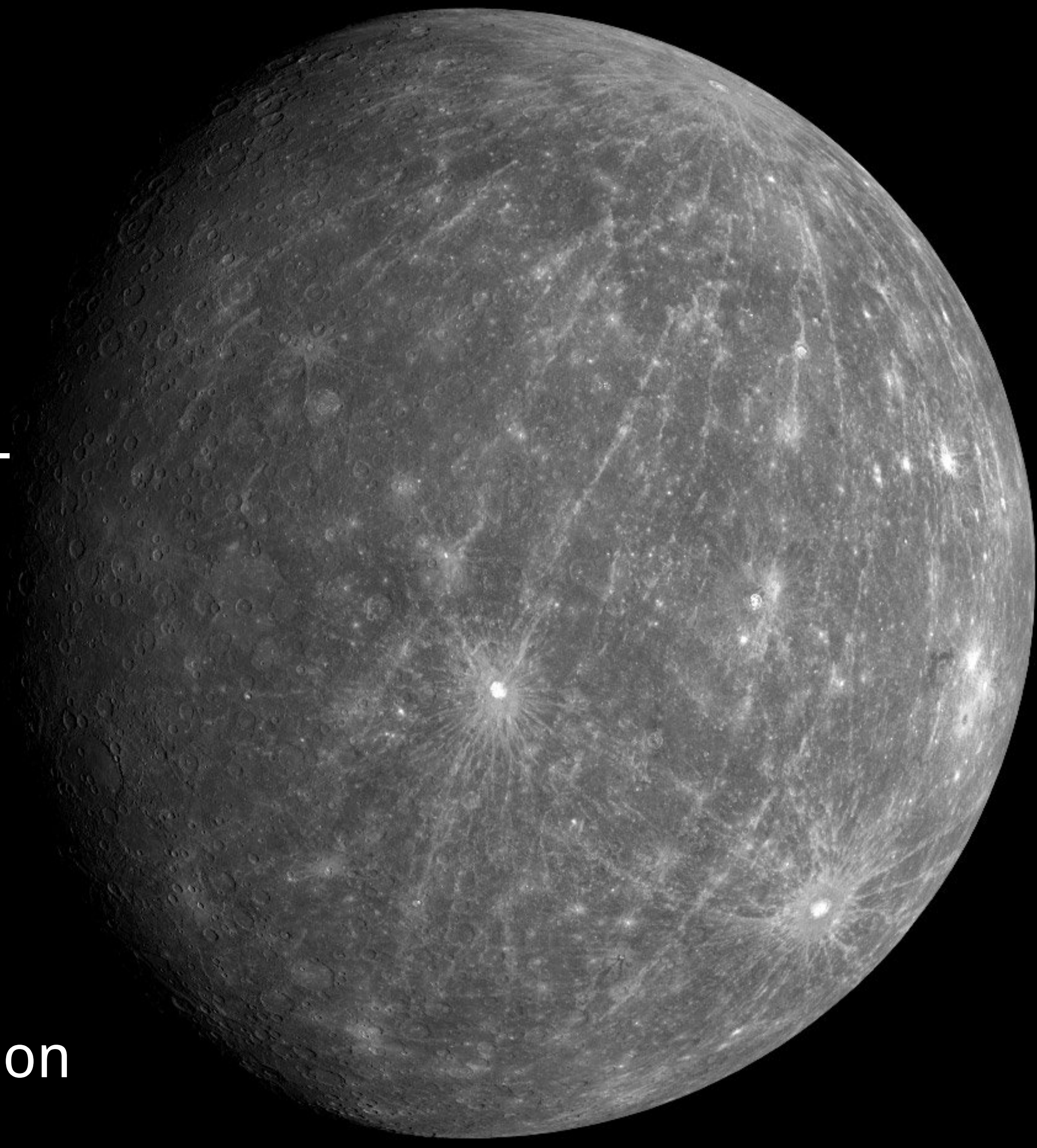
Density 5400 kg/m^3 – about the same as Earth

No atmosphere

No volcanoes

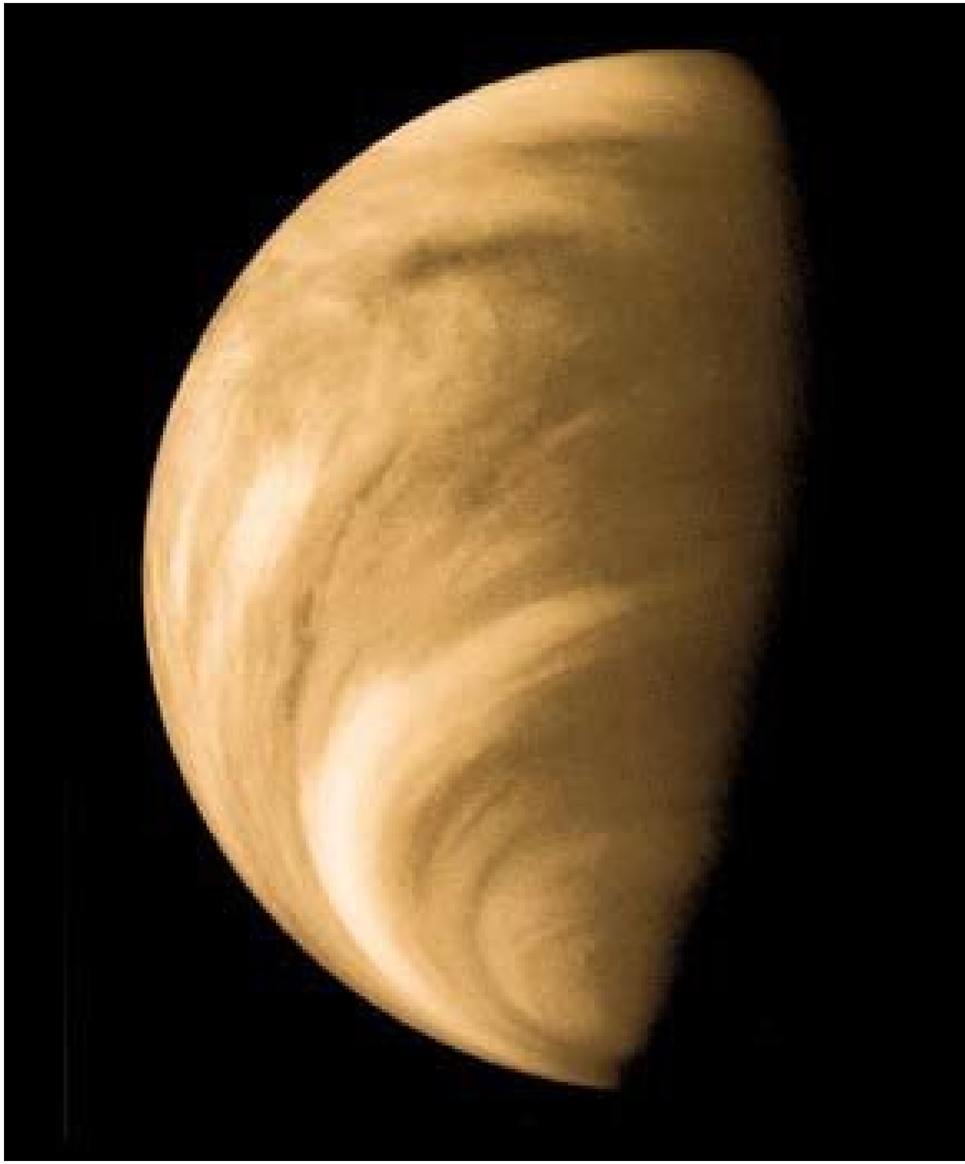
Has a magnetic field

Covered in craters similar to Earth's moon

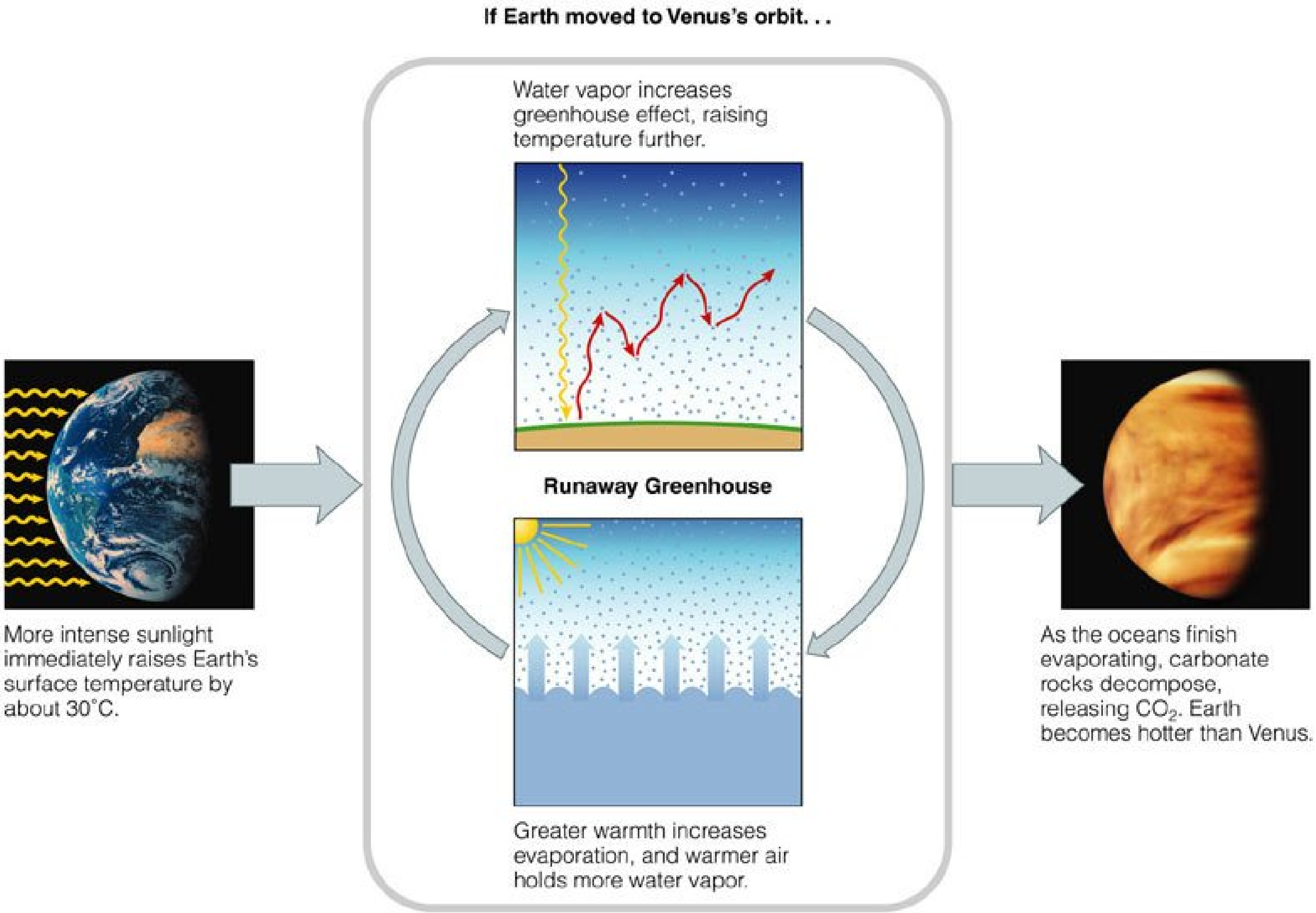


Venus

- Radius ~ 6100 km
- Mass ~ 82% of Earth
- Density ~ 5300 kg/m^3 – about the same as Earth
- Very thick atmosphere
- Many volcanic features, indirect evidence of current volcanic activity
- No magnetic field

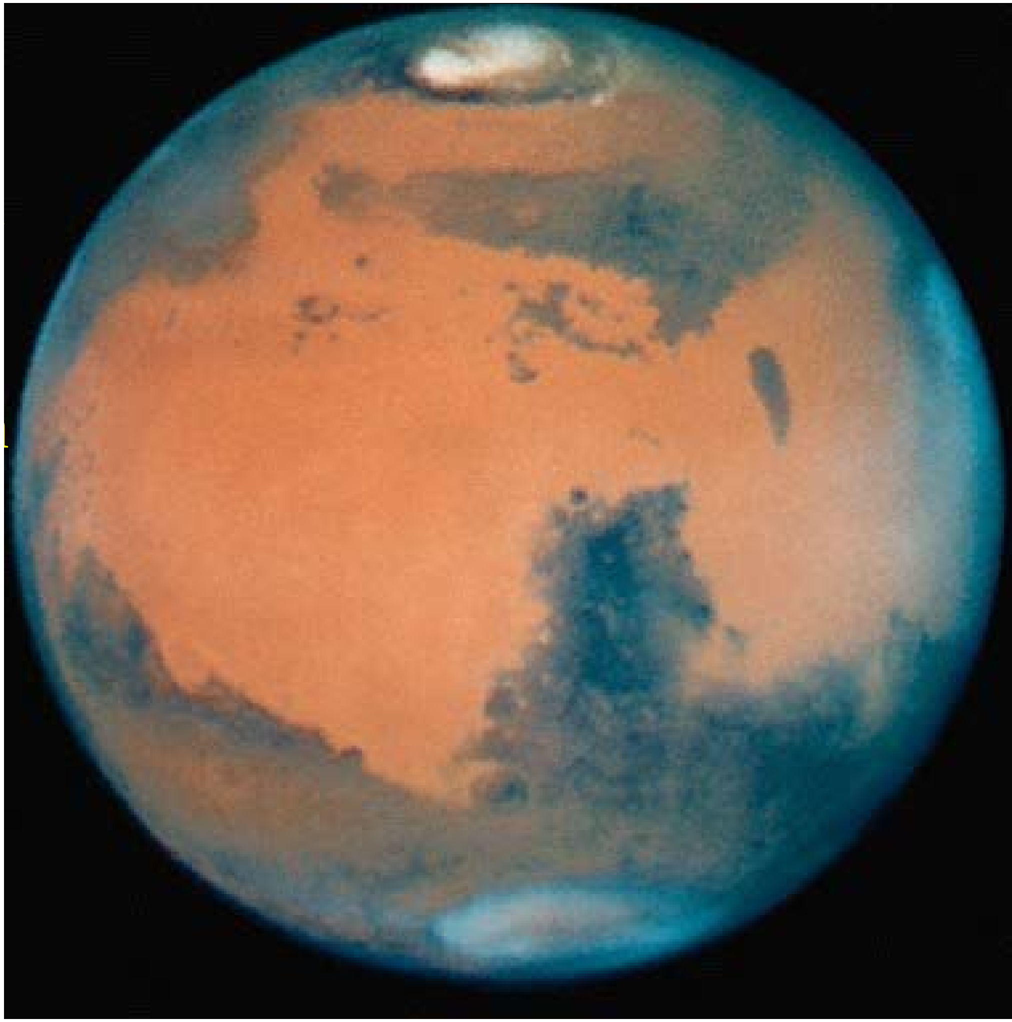


Runaway Greenhouse Effect

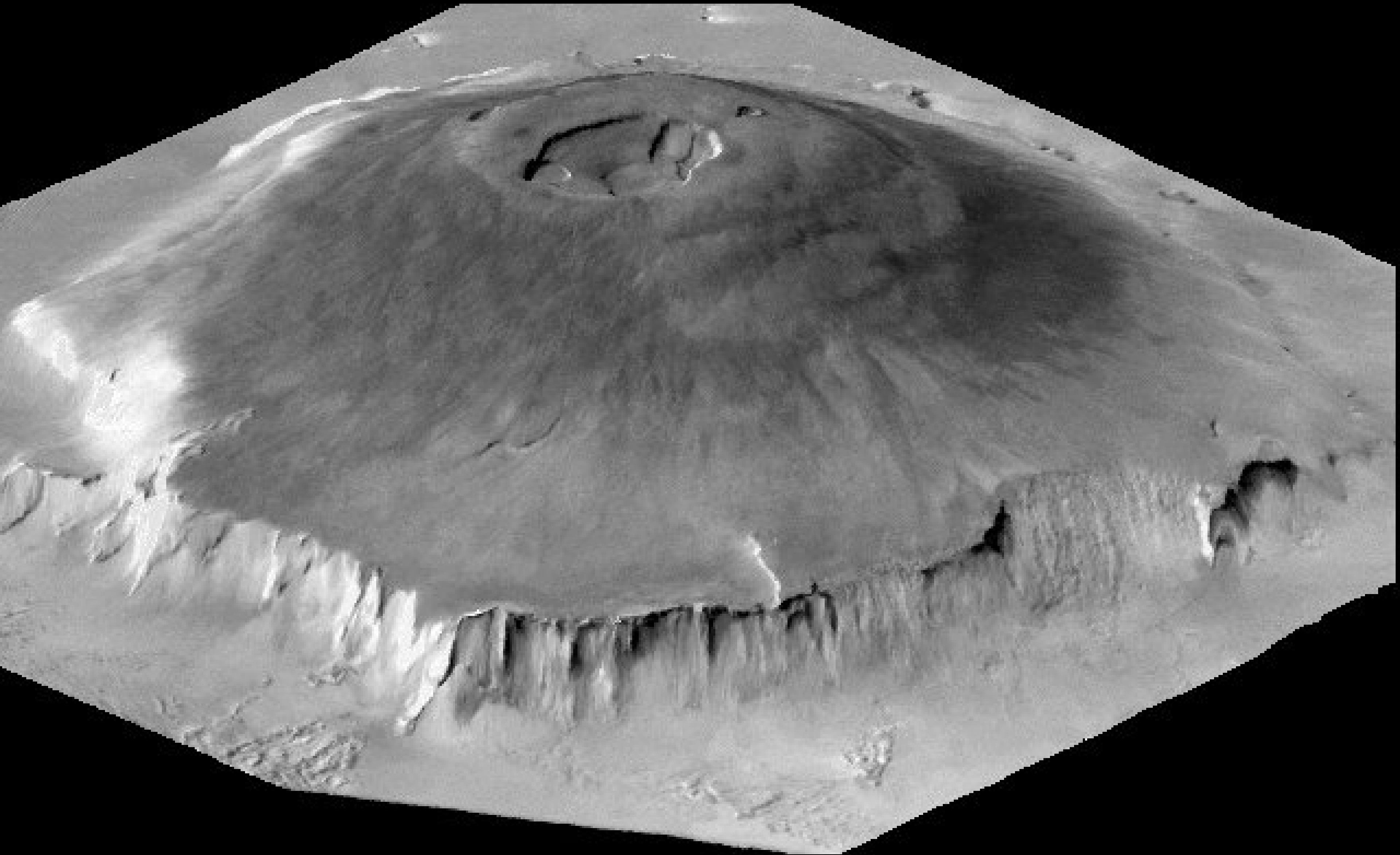


Mars

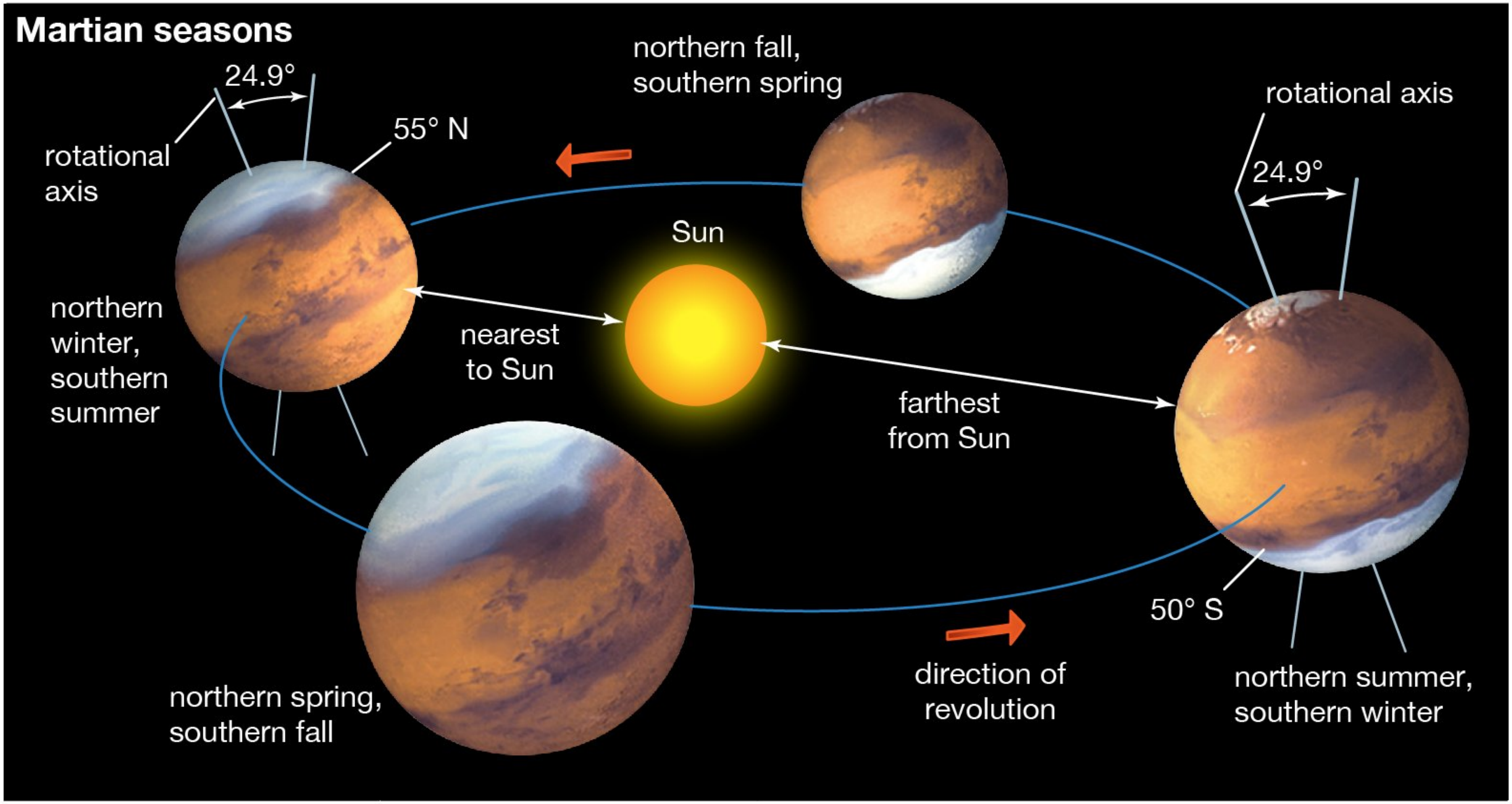
- Radius ~ 3400 km – ½ radius of earth
- Mass ~ 10% of Earth
- Density ~ 3900 kg/m^3 – smaller than Earth – density of rock.
- Thin atmosphere
- Extinct volcanoes
- No magnetic field



Olympus Mons

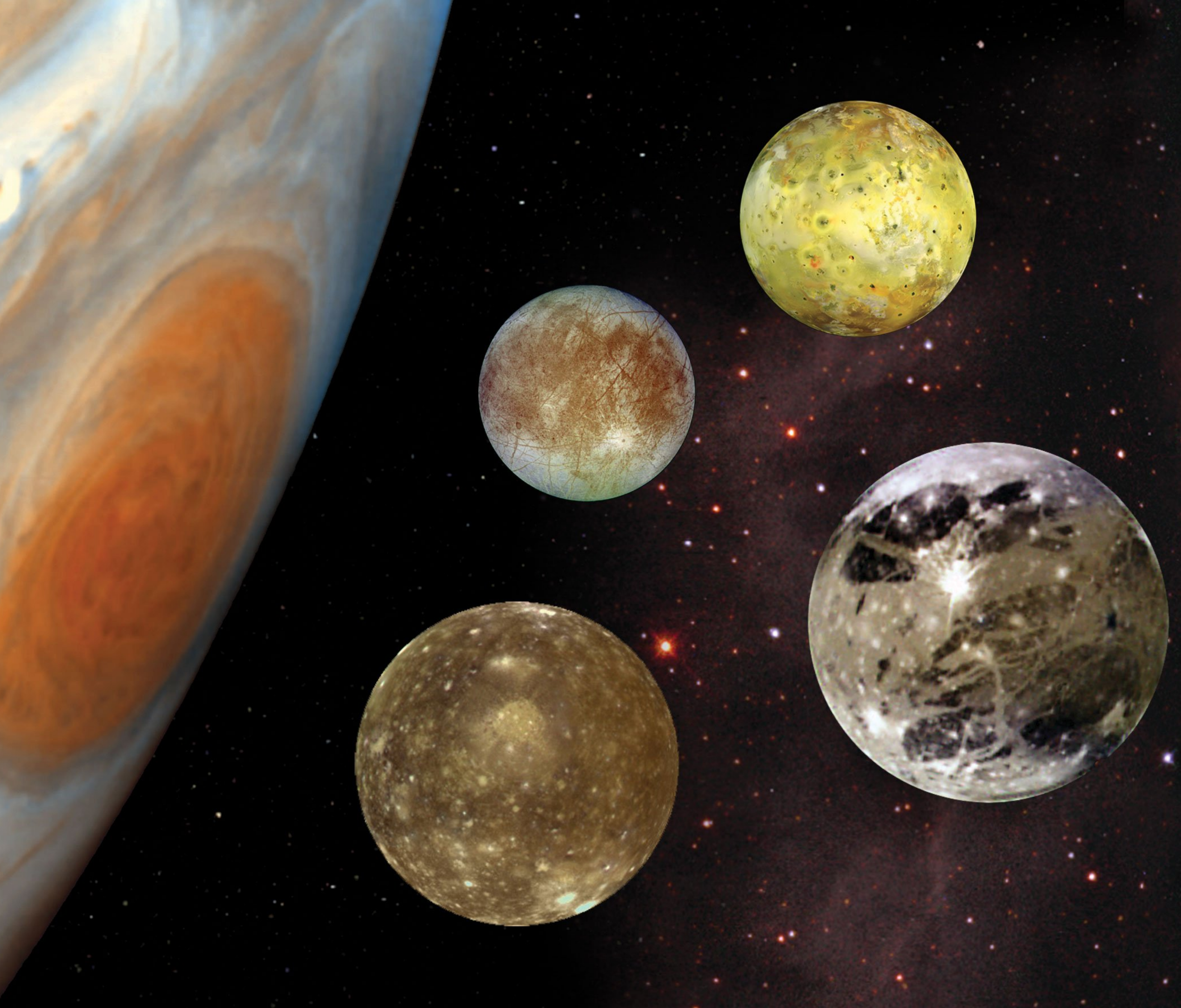


Seasons on Mars



Jupiter

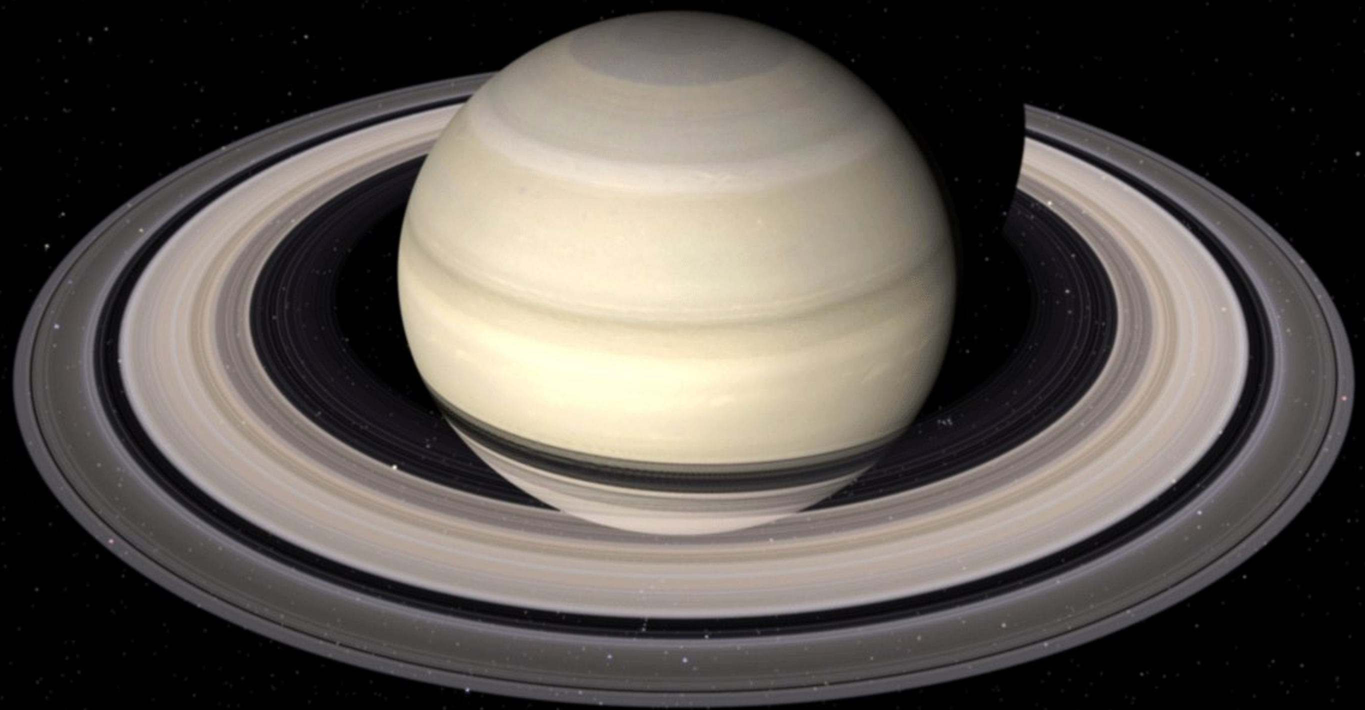
- Radius ~ 10 x Earth's
- Mass ~ 300 x Earth's
- Density ~ 1300 kg/m^3 –about same as water
- Composed of mainly hydrogen and helium
- No surface
- Strong magnetic field
- Rapid rotation ~ 10 hrs



1. Io
2. Europa
3. Ganymede
4. Callisto
5. Amalthea
6. Himalia
7. Elara
8. Pasiphae
9. Sinope
10. Lysithea
11. Carme
12. Ananke
13. Leda
14. Thebe
15. Adrastea
16. Metis
17. Callirrhoe
18. Themisto
19. Megaclite
20. Taygete
21. Chaldene
22. Harpalyke
23. Kalyke
24. Iocaste
25. Erinome
26. Isonoe
27. Praxidike
28. Autonoe
29. Thyone
30. Hermippe
31. Aitne
32. Eurydome
33. Euanthe
34. Euporie
35. Orthosie
36. Sponde
37. Kale
38. Pasithee
39. Hegemone
40. Mneme
41. Aoede
42. Thelxinoe
43. Arche
44. Kallichore
45. Helike
46. Carpo
47. Eukelade
48. Cyllene
49. Kore
50. Herse

Saturn

- Radius ~ 10 times Earth, mass ~ 100 times Earth
- Density ~ 700 kg/m^3 – less than water, Saturn would float!
- Composed of mainly hydrogen and helium
- No surface - Strong magnetic field



Uranus

Radius ~ 4 times Earth

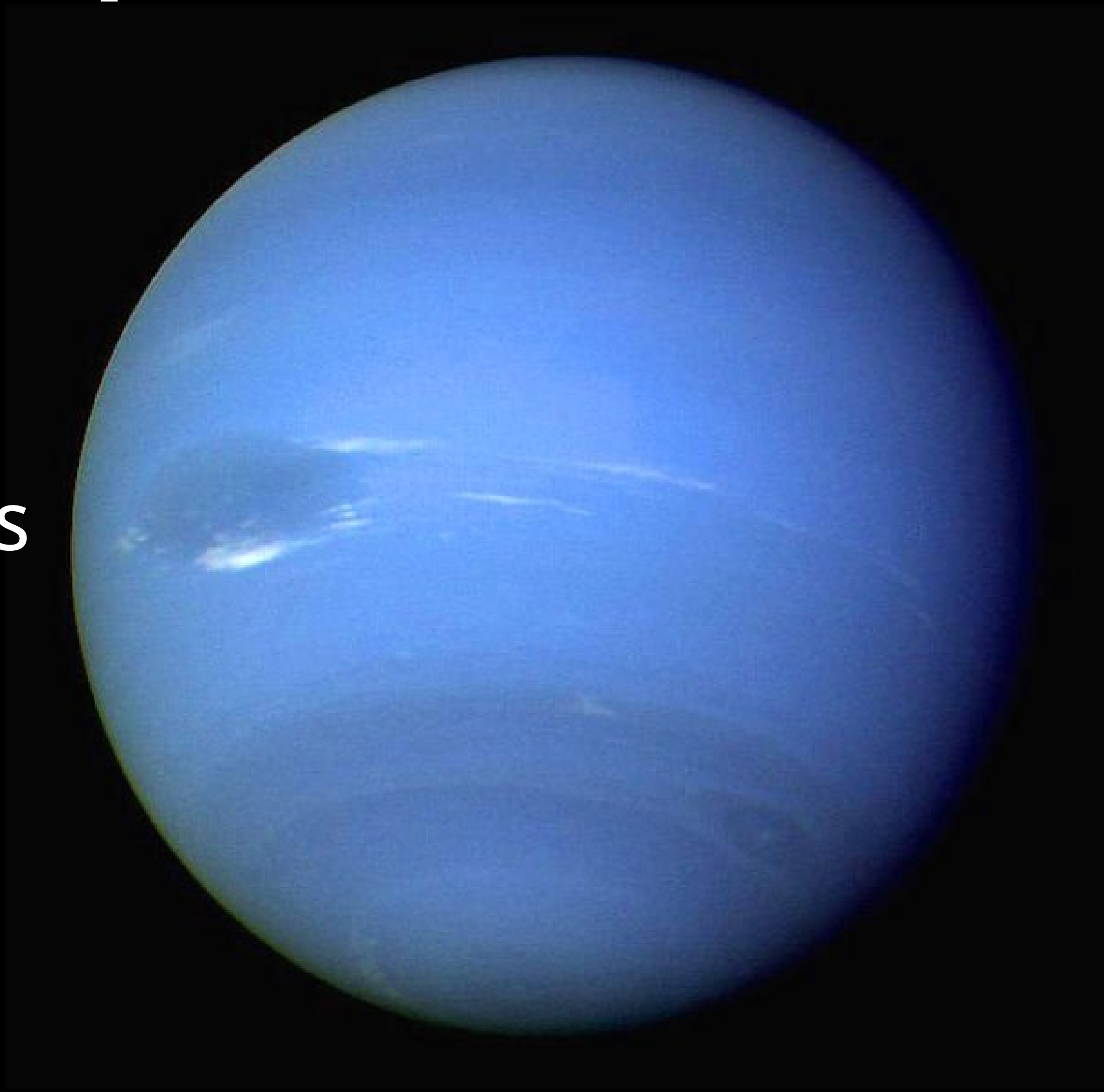
Mass ~ 15 times Earth

Nearly featureless – image at right is a false color image.

Rotation axis is tilted 98 degrees!

The tilt may be result of a giant impact (?)

Neptune



Radius ~ 4x bigger than Earth.

Mass ~ 17x Earth

Has bands of clouds unlike Uranus

Has a large storm on it called the Great Dark Spot.

Pluto and the Kuiper Belt

Pluto is only the second largest of the Kuiper belt objects. The largest is Eris.

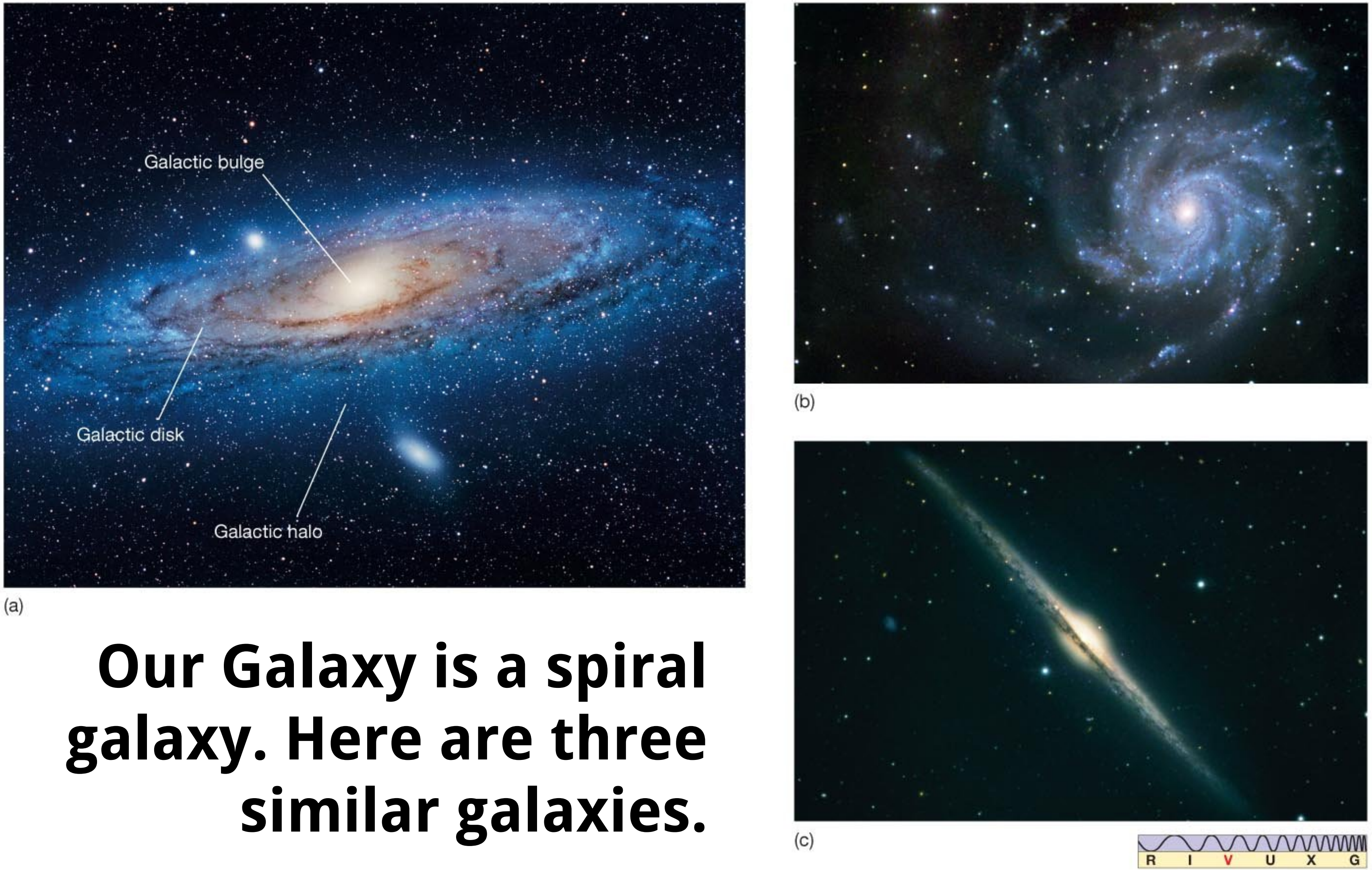
What is a galaxy?

A galaxy is a huge collection of stars that is isolated in space and held together by gravity.

We happen to live in one called the Milky Way Galaxy or just the Galaxy (with a capital “G”)

This is a picture of the Whirlpool galaxy – not the Milky Way

The Milky Way



(a) (b) (c)

Our Galaxy is a spiral galaxy. Here are three similar galaxies.

Standard Candles: Variable stars

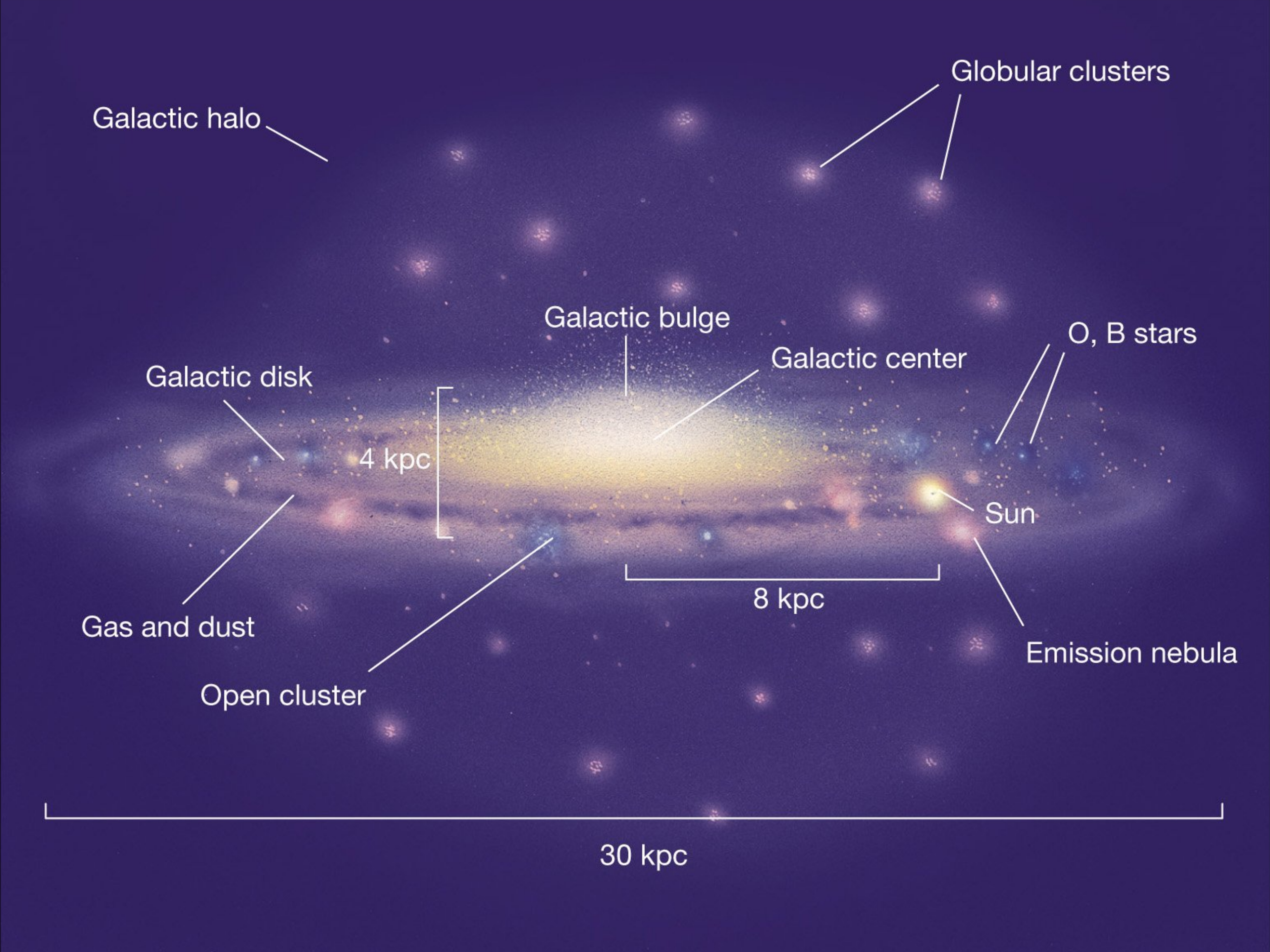
All stars oscillate. Oscillations are long sound waves, and the oscillation time is the time it takes sound to cross the star.

Large stars, like large bells, oscillate more slowly than small stars. Late in their evolution, bright stars have, for a short time, unusually large oscillations.

- Stars that take between 1-100 days to pulsate are call **Cepheids**.
- Stars that take less than 1 day are call **RR Lyrae** stars.
- Stars that take longer than 100 days are called **Mira variables**.

Summary of the distance ladder

- Use radar bouncing to find distances to Mars and Venus and so to find 1 AU
- Knowing 1 AU → use parallax to find the distance to stars within a few thousand light-years
- Knowing the distance to these stars, find the luminosity of main sequence stars.
  → Using main-sequence stars as standard candles, find the distance to stars throughout our galaxy.
- Knowing the distance to clusters of stars in the galaxy, find the luminosity of Cepheid variables.
  → Using Cepheid variables as standard candles, find the distance to galaxies outside the Milky Way.



Globular clusters
Galactic halo
Galactic bulge
O, B stars
Galactic center
Galactic disk
4 kpc
Sun
8 kpc
Gas and dust
Emission nebula
Open cluster
30 kpc

Structure of the Milky Way

- The **Galactic Disk** is home to most of the young stars in the Galaxy, and contains most of the dust and gas in the Galaxy
- The **Galactic Bulge** contains a mix of old and young stars
- The **Galactic Halo** has mainly old stars and is home to many globular clusters
- And the **Galactic Center** contains a supermassive black hole

Stellar populations: Old and new stars

Stars formed at the time the Galaxy formed are called **Population II** stars. They are almost entirely hydrogen and helium with few heavier elements, because the matter in them had not previously been in another star. They lie in all parts of the galaxy, the halo (globular clusters), disk, and bulge.

Younger stars, formed from matter in the disk of the galaxy, are called **Population I** stars. They are made from reprocessed material, matter that was once in other stars and was redistributed to the galaxy when the star died.

Population I stars are thus younger and begin their lives with a larger fraction of heavier elements than Population II stars.

(Astronomers are still searching for evidence of Population III, stars that do not have any elements heavier then Helium in their atmospheres.)

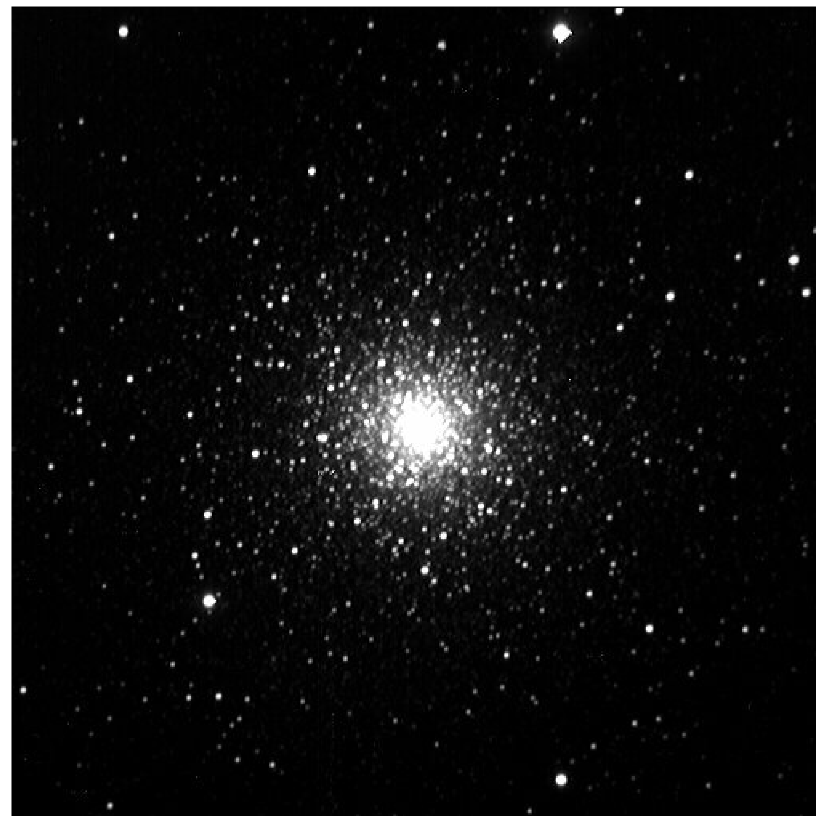
Population I and II stars

Both Population I and Population II stars are made mainly of hydrogen and helium. Even in Population I stars, like the Sun, heavier elements are a small fraction of the total mass.

Globular clusters formed at the time the galaxy formed. They are dense clusters of up to 1 million stars, all Population II.

→ Globular clusters are among the oldest objects in the universe.

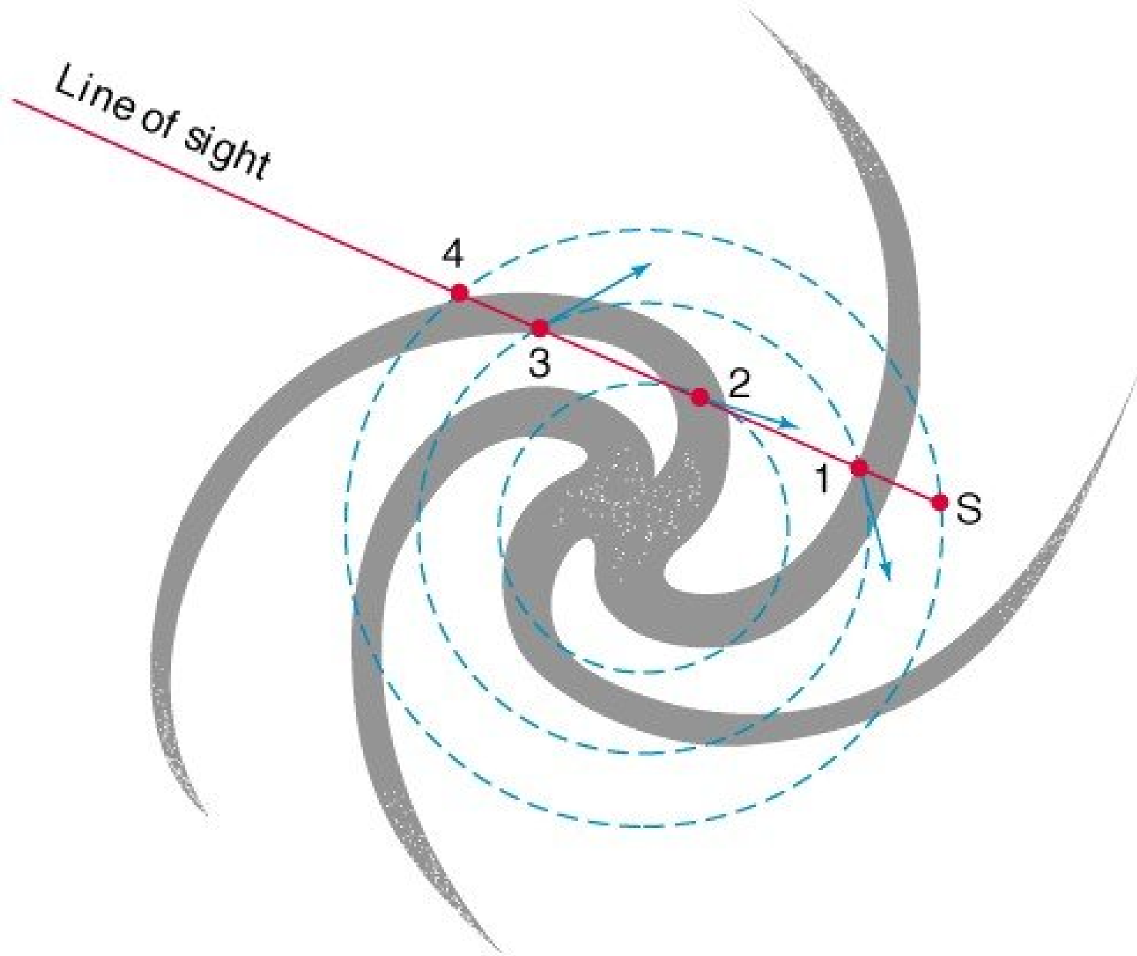
An example of a typical globular cluster is M3.



Mapping Milky Way's 21cm emission

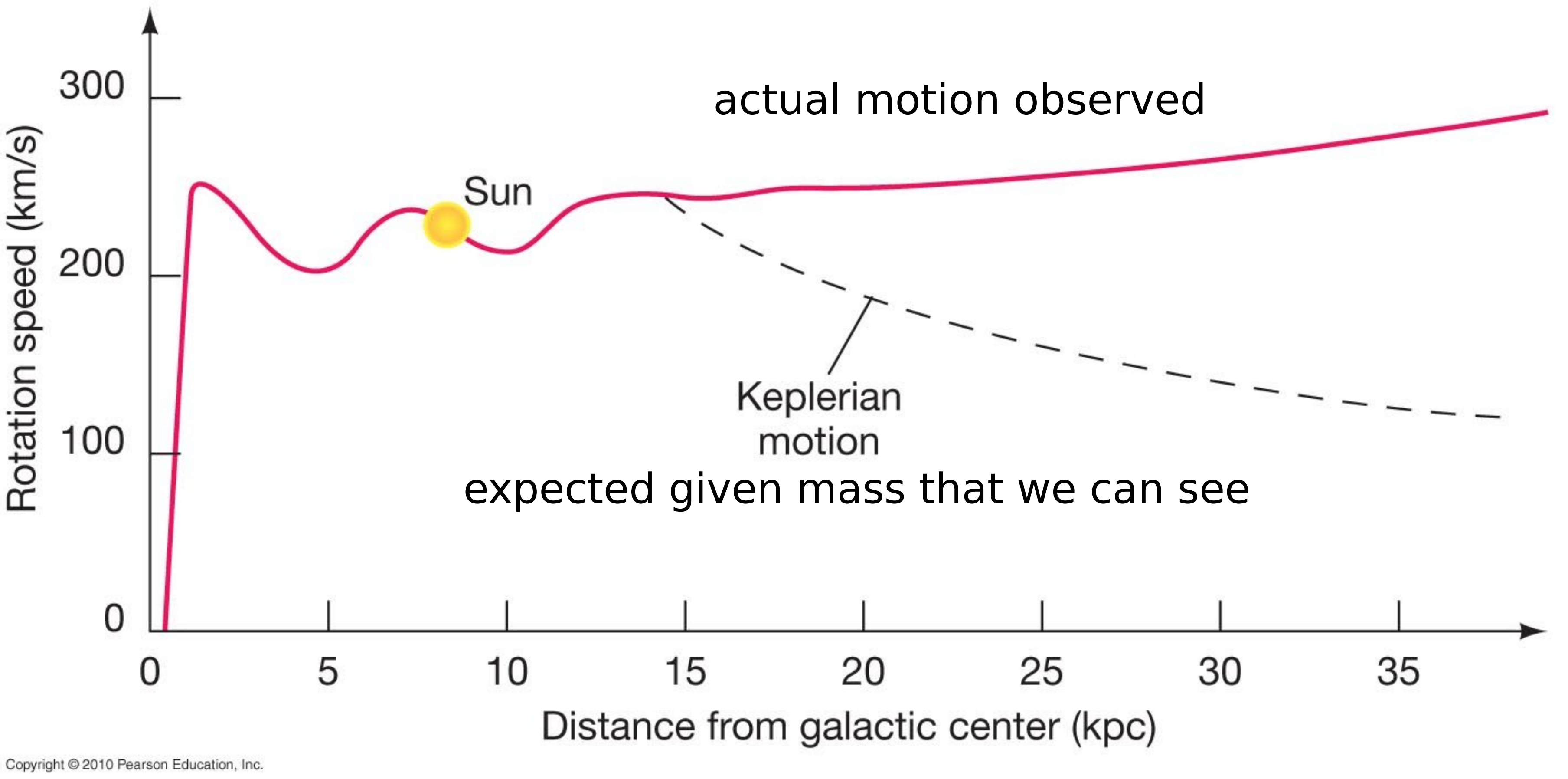
Cold hydrogen gas emits 21 cm radio waves (called 21 cm radiation), and this gas lives in the disk of the Galaxy

The Doppler shift is different from different parts of the arm (and different arms!)



Galactic rotation curve

Rotation curve of the Galaxy: How fast objects move as a function of the distance to the galactic center.



Rotation curve and Dark Matter

Instead, the speed at which stars, globular clusters and gas clouds orbit the galaxy implies a much larger mass than is visible:

Most of the Galaxy's mass is dark matter, matter too dim to see at any wavelength, that lies in the halo. We do not yet know what it is.

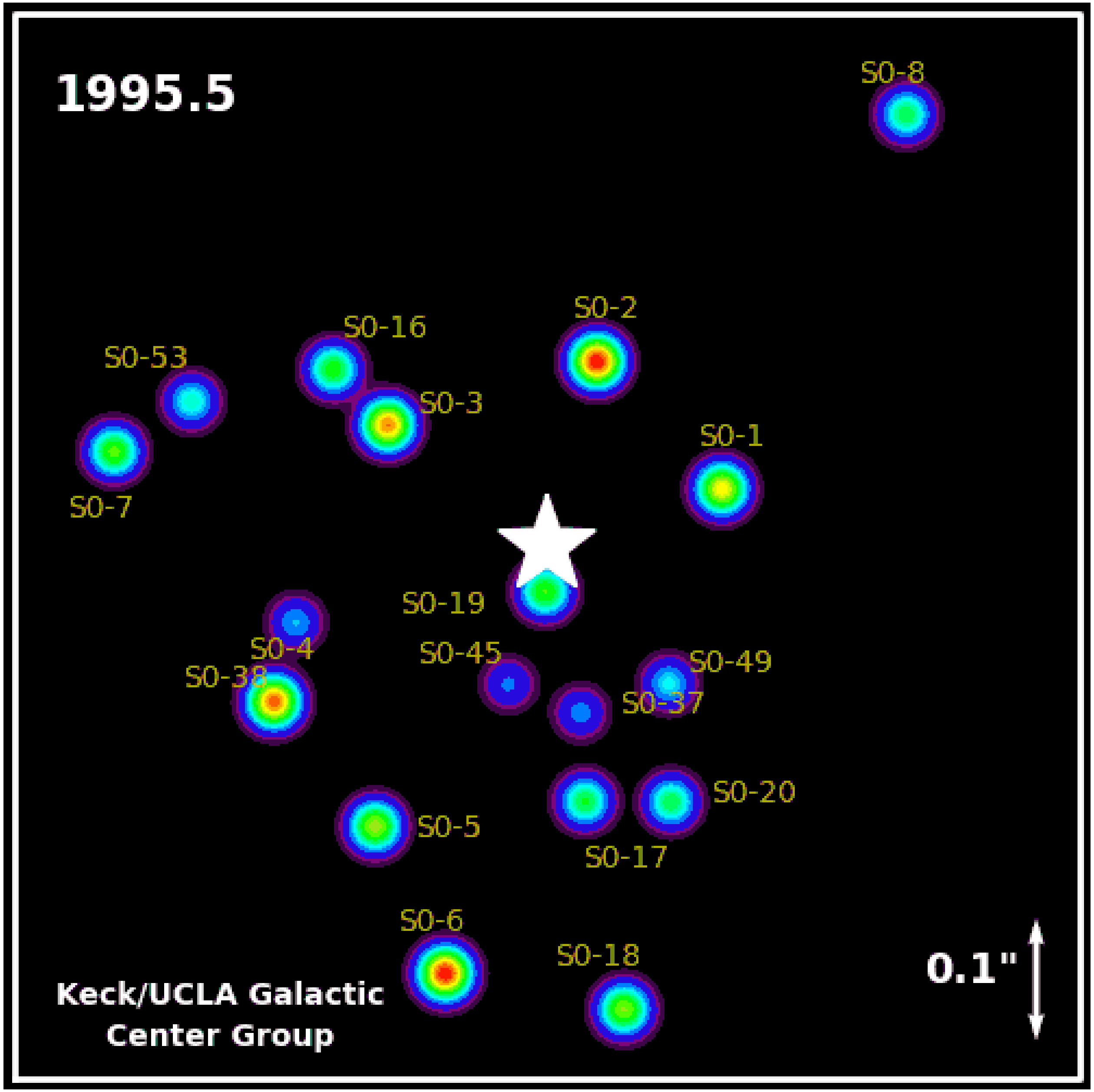
This is true of all other large galaxies whose mass we have measured. What constitutes most of the universe's mass is one of the most fundamental mysteries of current astronomy.

With 16 years of data, here's what the orbits look like

Recently the star S0-2 completed an orbit that we observed from start to finish

It comes very close to the center and moves very quickly

This is evidence that something very massive and dense lives in the center

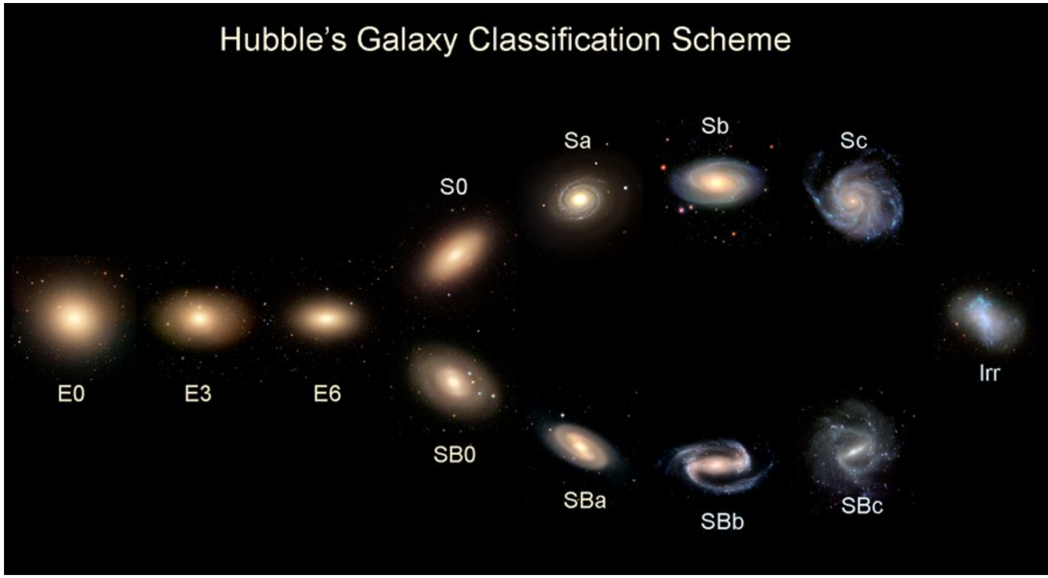


Hubble's Classification Scheme

Classification is based on a galaxy's appearance

Three main categories:

- Ellipticals
- Spirals: normal (S) and barred (Sb)
- Irregular



A galaxy's classification is called its Hubble type

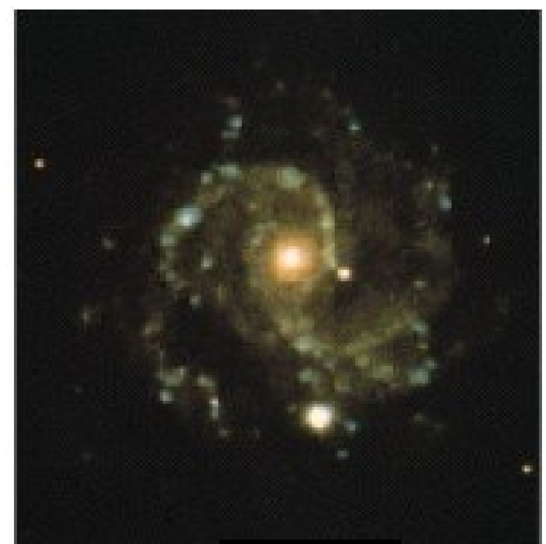
Spiral Structure

The Spiral structure can vary from galaxy to galaxy:

- Sa – weak spiral
- Sb – visible spiral
- Sc – prominent spiral

Sa

Sb



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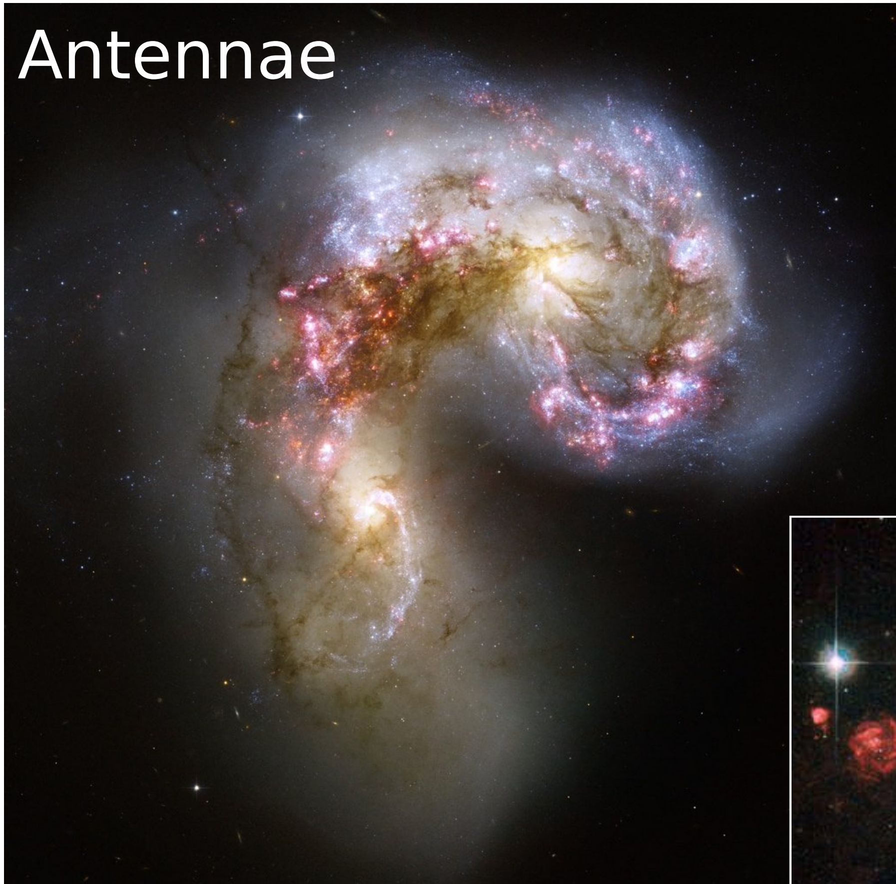
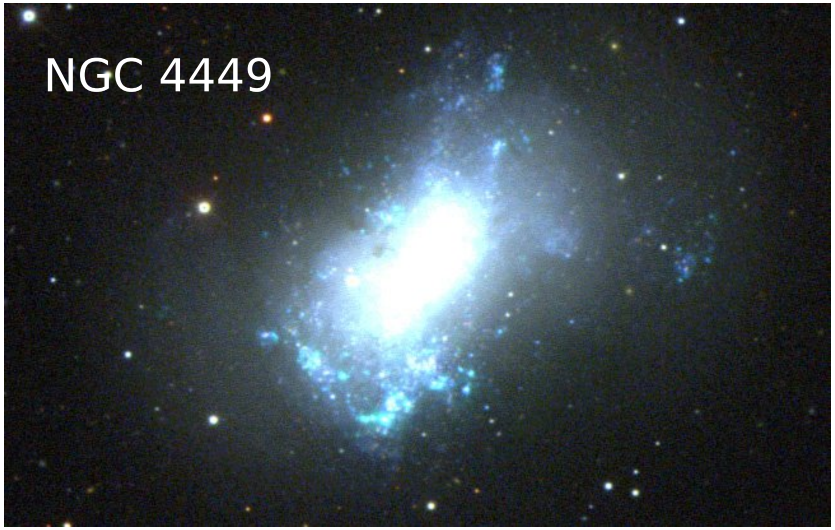
Elliptical Galaxies

The other major type of galaxy is elliptical

- These are spherical(ish) distributions of old stars
- Smooth – no distinct features and no disk
- Have older stars and little to no current star formation
- Similar to bulges of spiral galaxies, but larger

Irregular Galaxies





Usually small
Usually lots of gas and dust
Sometimes interacting

Collections of Galaxies

Galaxies are not distributed randomly throughout the universe – they are usually found in associations of galaxies called **groups** and **clusters**

- **Groups** are smaller associations, with usually less than 50 galaxies
- **Clusters** are larger and can contain thousands of galaxies – galaxy clusters are the most massive gravitationally bound objects in the universe

Galaxy clusters and groups

- Galaxy clusters and groups consist of a collection of galaxies orbiting one another, bound together by their own gravity
- The Milky Way, Andromeda, and several other smaller galaxies form the **Local Group**
- The nearest large galaxy cluster to the Local Group is the **Virgo Cluster**
- Galaxy clusters themselves tend to clump together into **superclusters**. The Virgo Cluster, the Local Group, and several other nearby clusters form the **Local Supercluster**

Hubble's Law

$v = H \times d$, $H = 70$ km/s/Mpc

Let's do a few examples.

- A galaxy is moving at 700 km/s away from us. How far away is it?
  - $d = v/H = 700/70 = 10$ Mpc
- A galaxy is moving at 21,000 km/s away from us. How far away is it?
  - $d = v/H = 21{,}000/70 = 300$ Mpc

What powers active galaxies?

The power source for active galaxies must be phenomenal

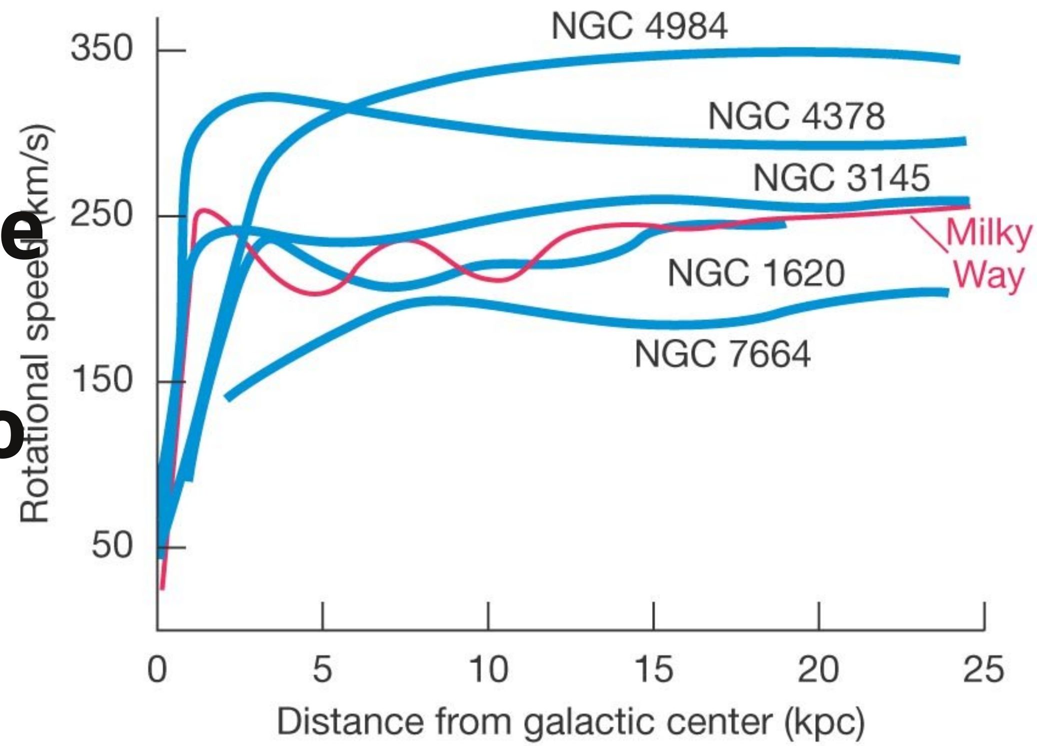
- They are bright. They are typically brighter than normal galaxies by a factor of 10^6-10^8
- They are compact – they vary on short (1 week – years) timescales, so they can be at most 1 light-week to light-years in size
- Doppler shifts of spectral lines show evidence of motion with velocities of ~ 10,000 km/s: very fast!

The only power source that can explain all of this is a **supermassive black hole**.

Rotation Curves of Galaxies

What we find is that as we move away from the center of a galaxy, the rotational speed tends to flatten to a constant speed

This means that **the mass of the galaxy continues to increase even in areas where there are very few to no stars**



(b)

Dark Matter

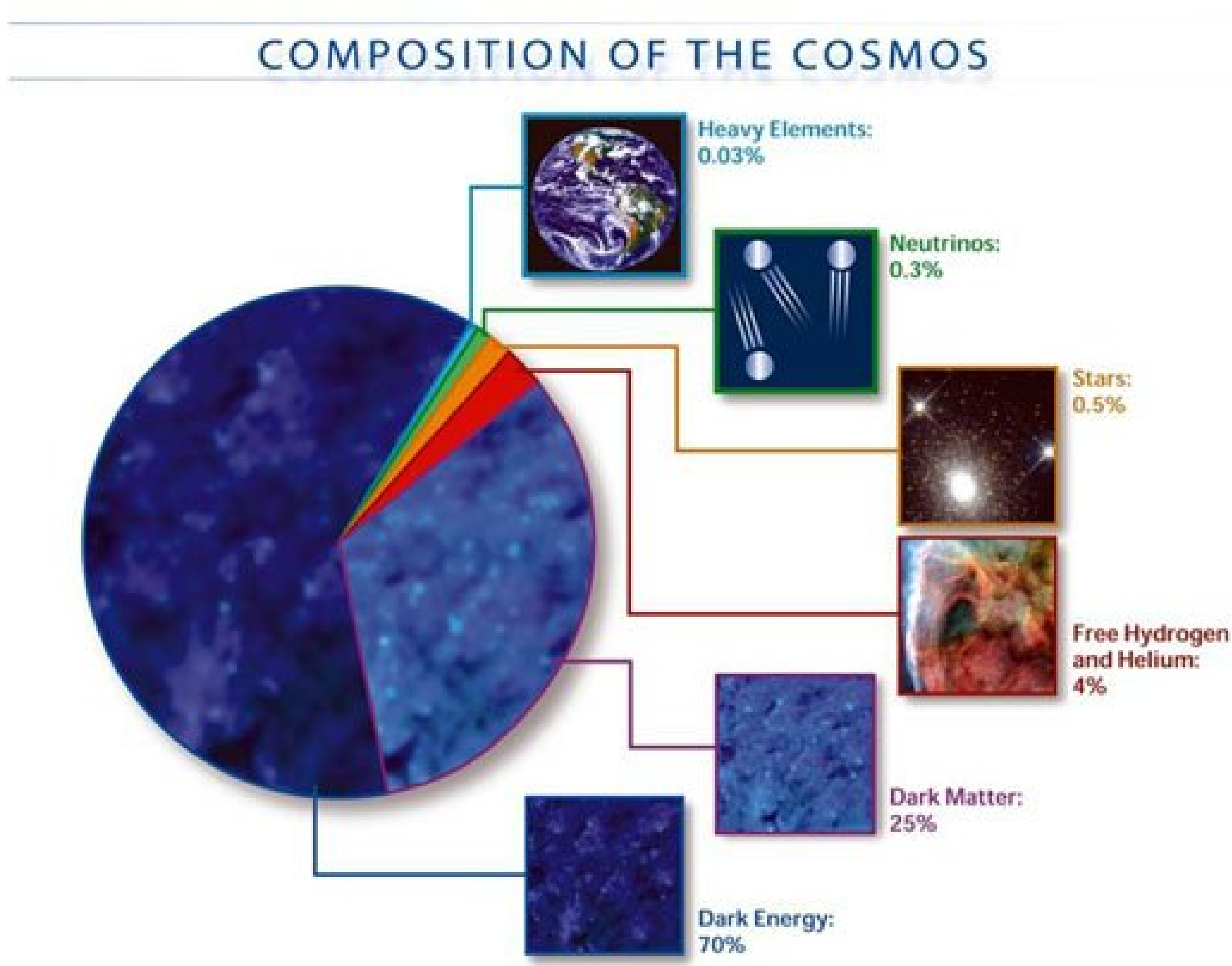
So the combination of all these measurements means that there is a lot more **gravitating** mass than visible mass in the universe.

- Flat rotation curve of galaxies
- Orbital speed of galaxies in clusters
- Gravitational lensing (more on this later)

This matter is known collectively as **dark matter**.

It is generally though to be a particle that doesn’t interact with ordinary matter, but even this is not known – could be several particles.

The Makeup of the Universe



In fact about 95% of the universe is invisible!
And 23% of it is **dark matter**.