Astronomy

Final 3 Weeks of 2026 School Year

Weeks 18 - 20

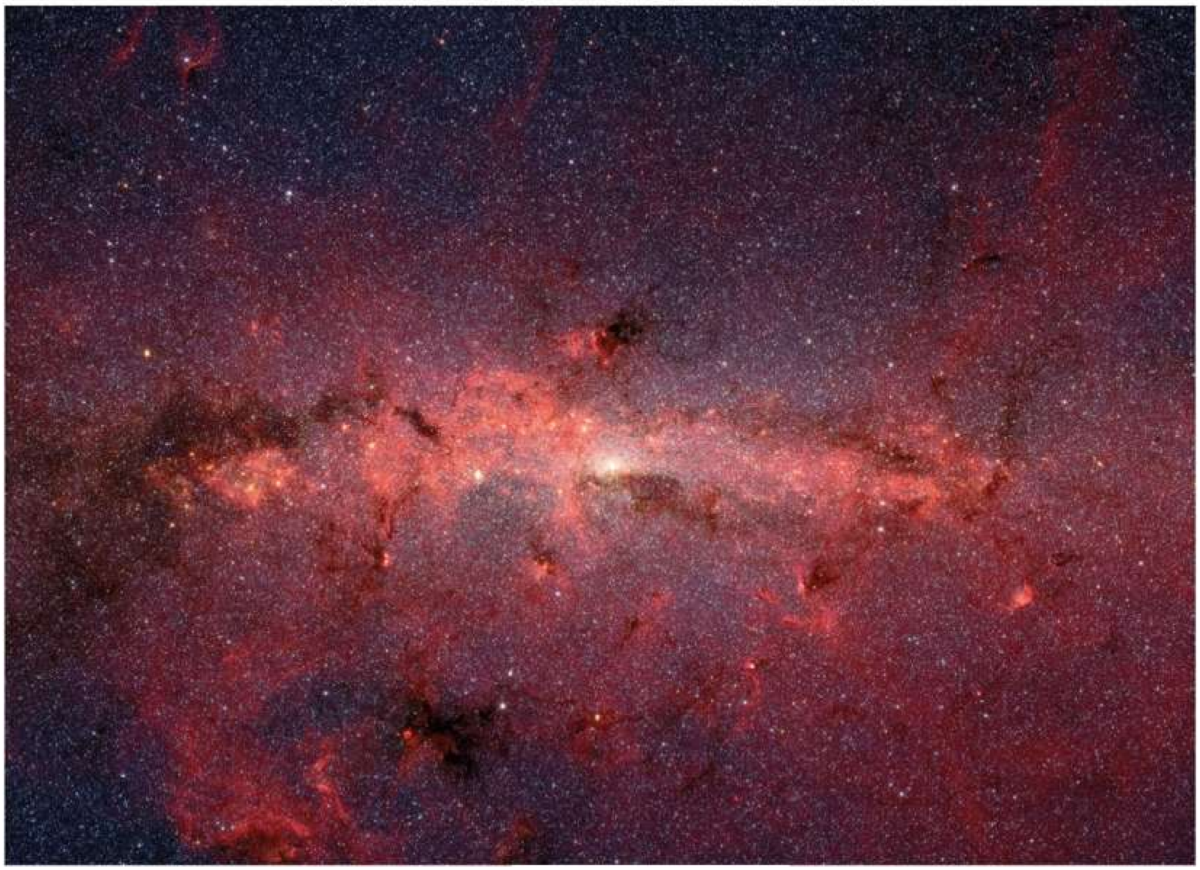
Monday / Tuesday (5/11 & 12)

- T: **(14) Science concepts. The student knows the structure of the universe and our relative place in it. The student is expected to:**

(A) illustrate the structure and components of our Milky Way galaxy and model the size, location, and movement of our solar system within it;

- O: I will begin to understand the Milky Way
- D: by taking notes, participating in a class discussion, and answering video questions.
- A: Milky Way
- Y: What are some important physics aspects of the Milky Way?

The Milky Way Galaxy

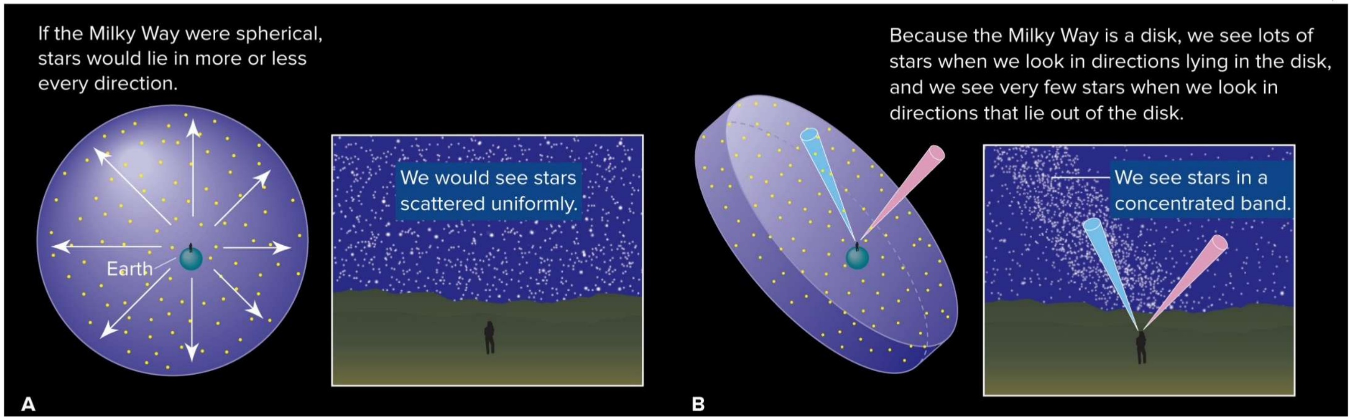


- NASA/JPL-Caltech

The Milky Way

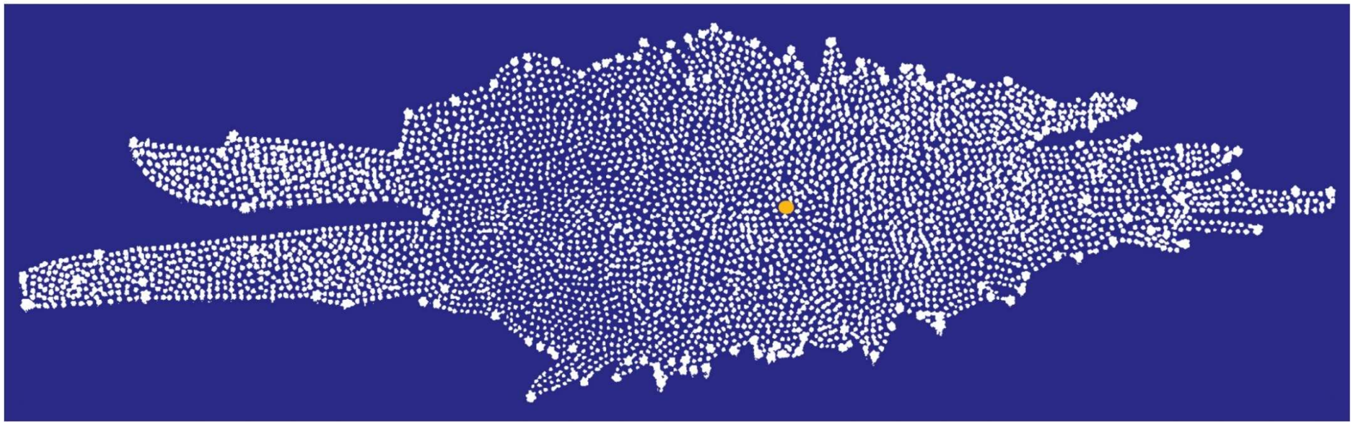
- The pale band of light spangled with stars stretching across the sky is the ***Milky Way,*** a swath of light named by the ancient Greeks.
- In the 17^{th} century, Galileo showed the Milky Way is millions of stars too dim to see individually.
- Today we know the Milky Way is a slowly revolving disk of stars, a galaxy.
- We also know today that the Milky Way is filled with stars of various sizes, many of them found in clusters, and clouds of gas and dust.

Shape of the Milky Way



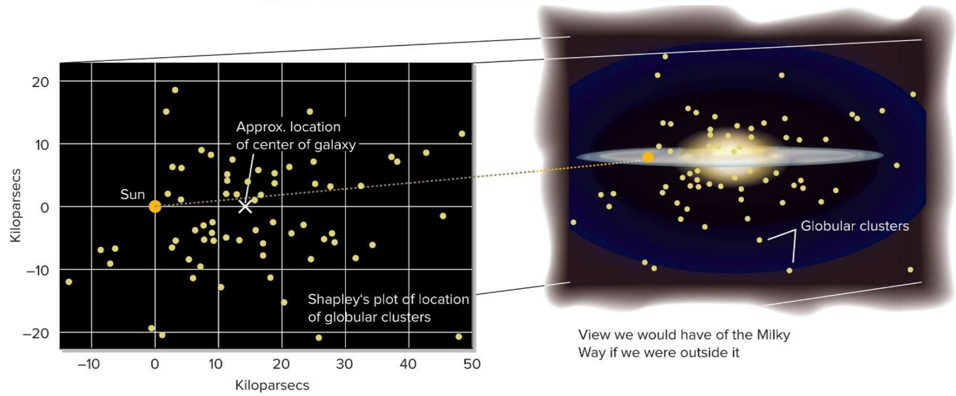
- Uniform distribution of stars in a band across the sky lead Thomas Wright, Immanuel Kant, and William Herschel in the 18th century to suggest the Milky Way is a disc distribution of stars with the Sun near the center.

Early View of the Milky Way



- William Herschel's sketch of the Milky Way, from 1748. This sketch led Herschel (and others) to believe the Milky Way was disk-shaped (correct), and that the solar system was near the center of that disk, at the position of the yellow dot (incorrect).

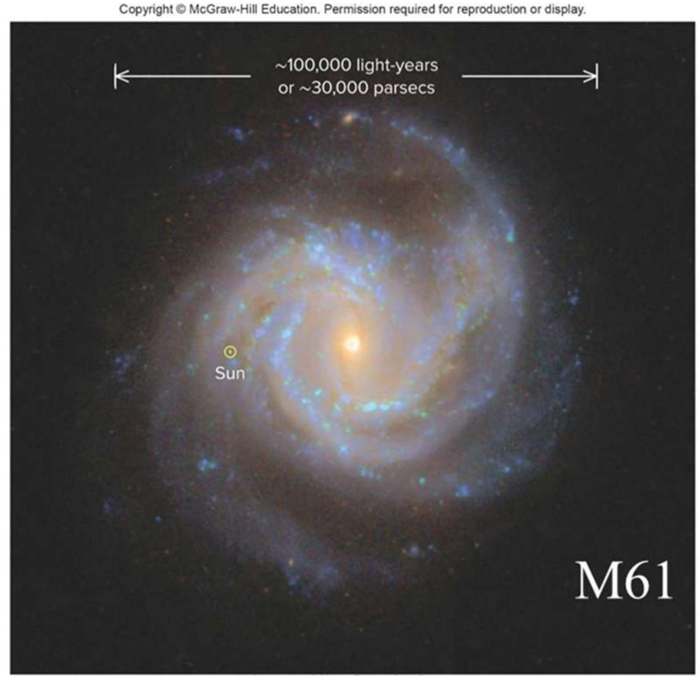
Finding the Galaxy's Size



- Jacobus Kapteyn determined the diameter of the Milky Way to be 20 kpc with the Sun near the center.
- Harlow Shapley found the diameter to be 100 kpc with the Sun ⅔ from the center.
- Both were not aware of the dimming effects of dust.
- Shapley, using globular star clusters for distances, did not distinguish RR Lyrae from Cepheid variables.

Size of the Milky Way

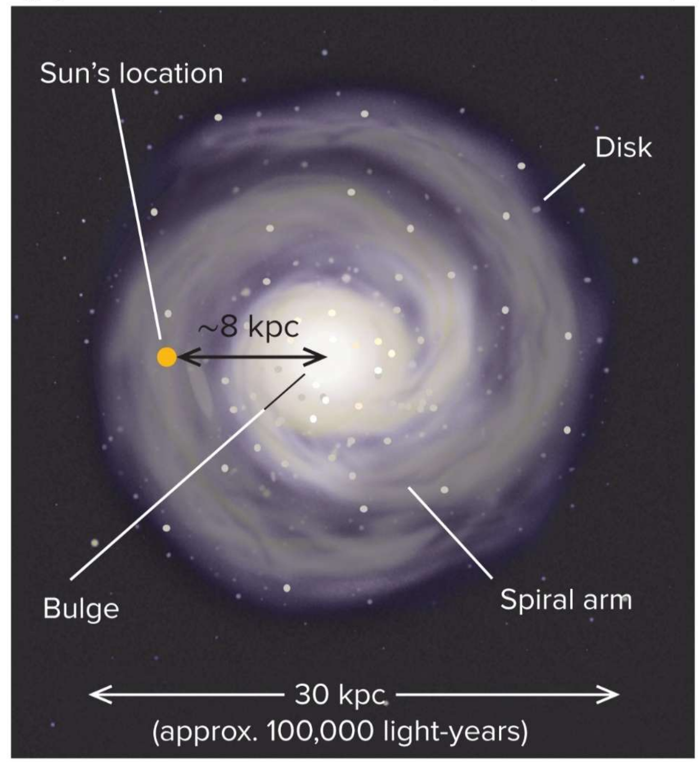
- Correcting for dust effects and variable star types, astronomers conclude the disc has a 30 kpc diameter with the Sun ⅔ from the center.
- Discovery that nearly all disc-shaped galaxies have spiral arms implied Milky Way is a spiral too.



- Courtesy of Sioan Digital Sky Survey

Structure and Contents of the Milky Way

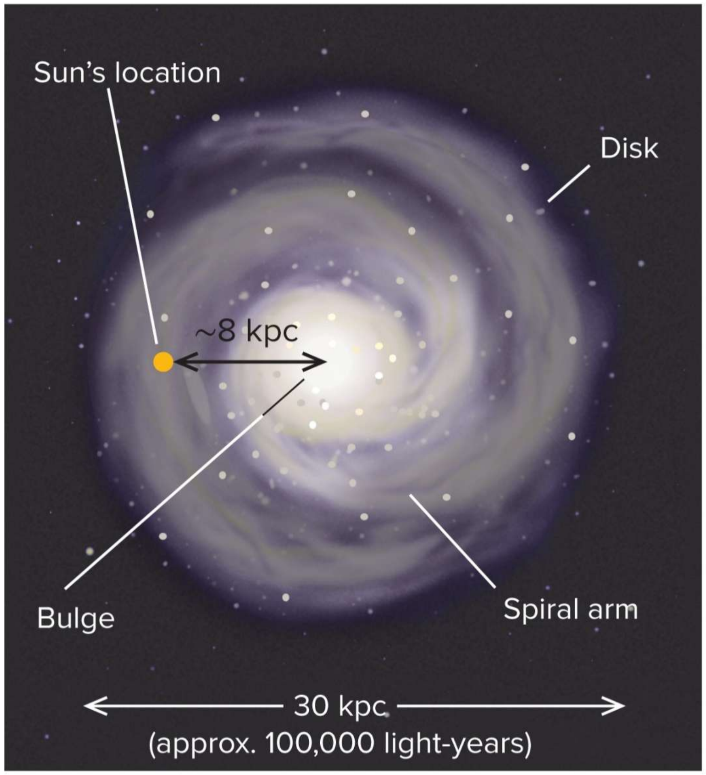
- The ***Disk.***
- ***Spiral arm*** distribution of stars, gas, and dust with a diameter of about 30 kpc (100,000 light-years) and plane tilted with respect to Earth's orbit around Sun.
- Differential rotation with all objects circling in the same direction: 240 million-year period at 220 km/sec at the Sun's orbit (about 8.5 kpc out from center).



Top view

Disk Composition

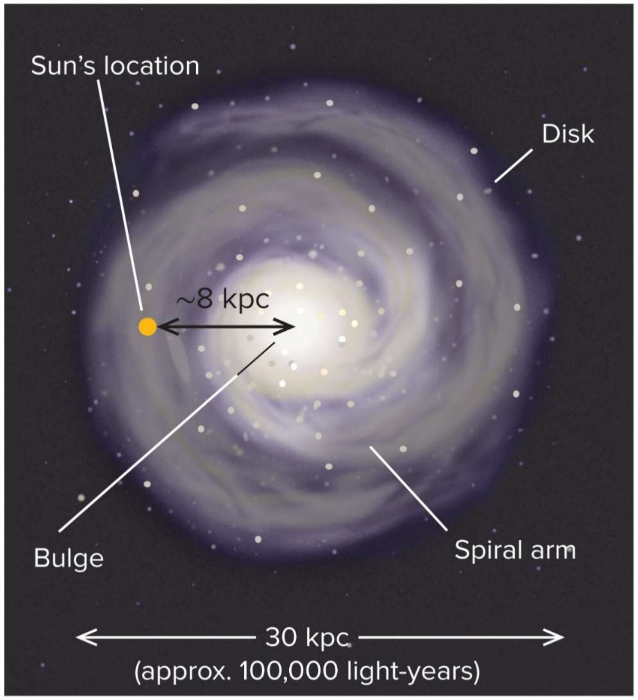
- The ***Disk***.
  - High density of stars near center (10 million stars per cubic light-year) to low density farther out (0.003 stars per cubic light-year at Sun).
  - Dust and gas is nearly 15% of the disc's mass.



Top view

Dust in the Disk

- The ***Disk.***
  - Most of galaxy is hidden from Earth due to dust obscuration including the central ***nucleus*** with its dense swarm of stars and gas in which a massive black hole may reside.
  - Radio and infrared telescopes can “see” entire galaxy: Radio observations suggest larger warped disc of gas (out to nearly 40 kpc).

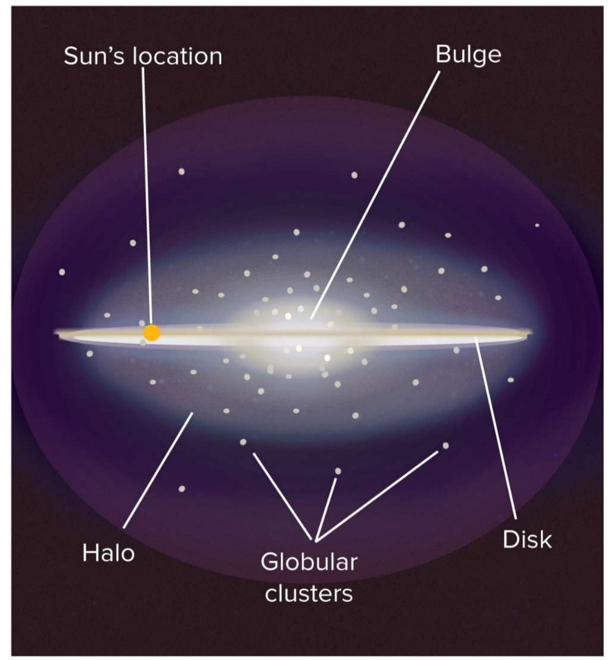


Top view

The Halo and Bulge

- ***Halo.***
- Roughly spherical region with disk embedded.
- Contains mainly old stars, such as globular clusters.
- Large amounts of dark matter may also be present.

- ***Bulge.***
  - Flattened collection of stars surrounding dense core of galaxy.
  - About ⅓ the diameter of the galaxy.



Side view

The Role of Gravity

- Gravity holds all of these components together.
- Stars near the center of the galaxy move faster than those near the edge, as expected.
- This is called **differential rotation**.
- The Sun and its neighbors move around the center of the galaxy at 220 km/s.

- Courtesy of Sioan Digital Sky Survey

Composition and Mass of the Milky Way

- From its rotation and effects on nearby galaxies, mass of Milky Way is $2 \times 10^{12} M_{\odot}$.
- From large difference between this mass and what is observed, astronomers conclude Milky Way is embedded in vast halo of material that emits no radiation (at any wavelength) – ***dark matter.***
- Assuming that the average star has a mass similar to that of the Sun, then based on the Milky Way's mass, there are roughly 100 billion stars.

Age of the Milky Way

- Using stellar aging techniques, astronomers had estimated the galaxy's most ancient stars to be about 13 billion years old.

- © David Main/Australian Astronomical Observatory

Stars of the Milky Way

- Stellar Censuses
  - Counts that list all known stars of a given type in a region of space is called a stellar census.
  - All star types are represented in the Milky Way.
  - By analyzing the relative numbers of stars of each type, deducing the galaxy's history is possible.

The Mass Function

- From a stellar census, one can derive the number of stars of each mass, known as the ***mass function.***
- Mass determines the life cycle of a star.
- The evolution of the Milky Way will then depend on:
- How many stars of each type it contains (A galaxy with only massive stars will evolve quickly).
- How fast each type is created (Fast creation will quickly deplete gas resources).

Wednesday / Thursday (5/13 & 14)

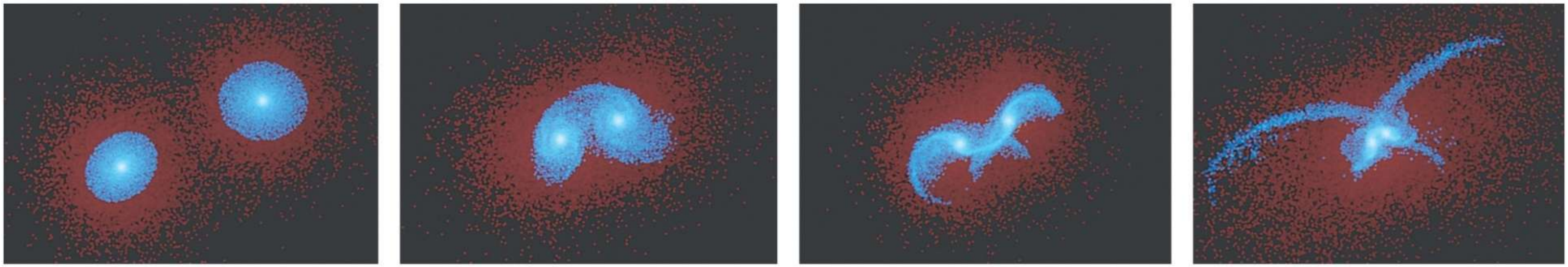
- T:14 (B) compare spiral, elliptical, irregular, dwarf, and active galaxies; (C) develop and use models to explain how galactic evolution occurs through mergers and collisions;
- O: I will increase my understanding of galaxies and how they move and collide
- D: by taking notes, participating in a class discussion, and creating my own galaxies with a simulation.
- A: spiral, elliptical, irregular
- Y: How do galaxies interact with one another?

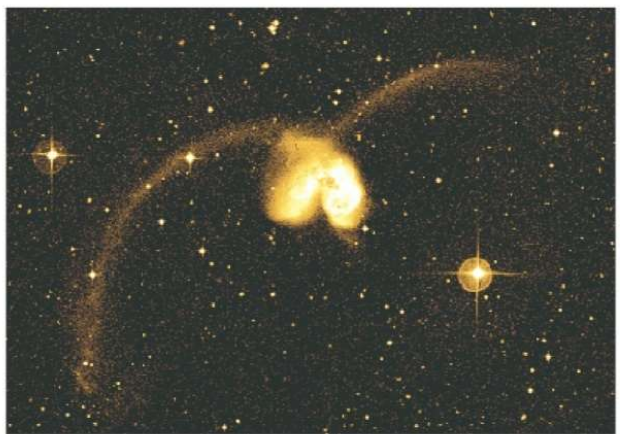
Galactic Cannibalism

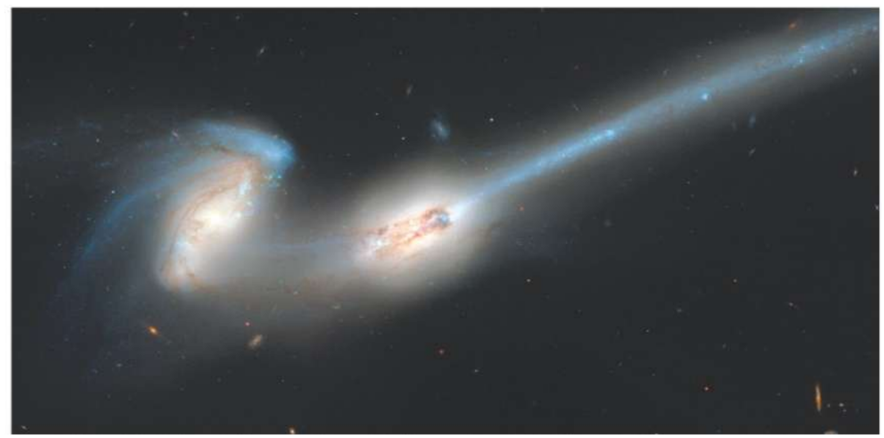
- Evidence for galaxy type change via collisions/mergers over time.
- On a large scale, small galaxies may be captured and absorbed by a large galaxy in a process called ***galactic cannibalism.***

- Explains abnormally large ellipticals in center of some galaxy clusters.
- Milky Way appears to be “swallowing” the Magellanic Clouds, while Andromeda shows rings and star clumps of “swallowed” galaxies.
- This process may allow ellipticals to turn back into spirals.

Galactic Collisions and Mergers



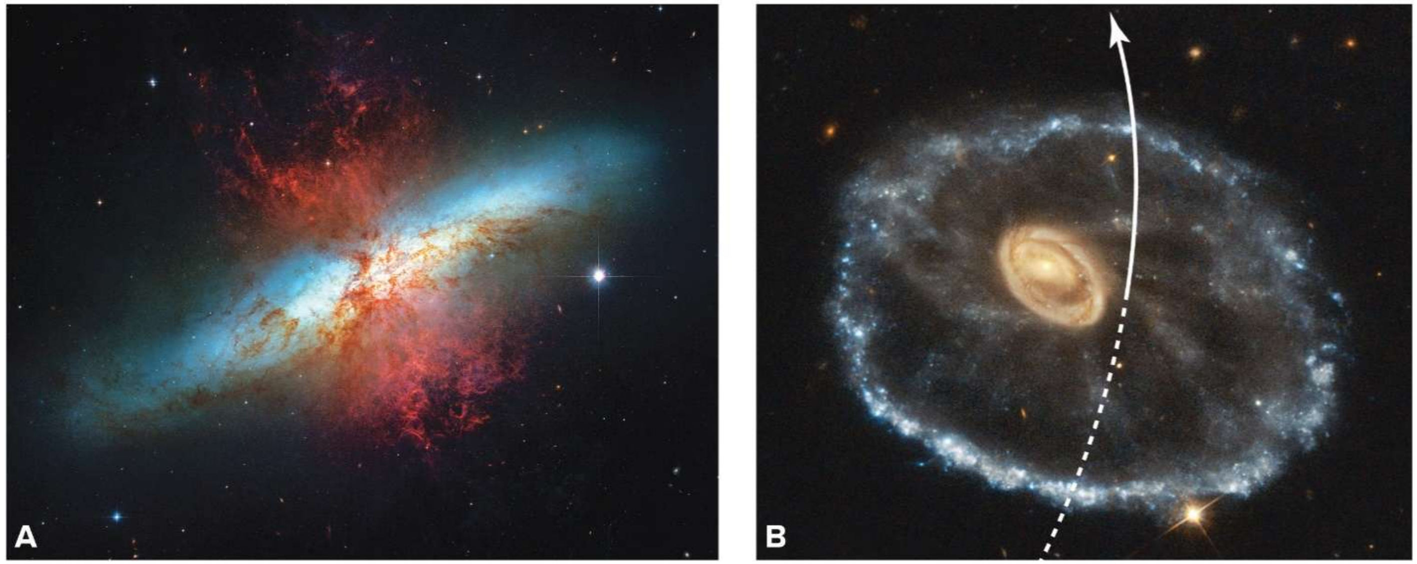




• (top row & bottom, left): Courtesy of Joshua Barnes, University of Hawaii; (bottom, right): NASA, H. Fort (JHU), G. Illingworth (USCS/LO), M. Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA

- Could galaxy’s type change with time?
- Computer simulations show a galaxy’s shape can change dramatically during a close encounter with another galaxy.
- Evidence (faint shell-like rings and dense clumps of stars) of spirals colliding and merging into ellipticals.

Consequences of a Collision



- Individual stars are left unharmed—too far apart to collide—but planet orbits may be affected by close passes of other stars.
- Gas/dust clouds collide triggering a burst of star formation (a starburst), especially in gas-dense regions.
- A small galaxy may alter the stellar orbits of a large spiral to create a “ring galaxy.”

- a: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); b: Source: STScI and NOAO

Stellar and Gas Content of Galaxies

- Spirals
  - Star types: Mix of Pop I (younger metal rich) and Pop II (older metal poor).
  - Interstellar content: 15% by mass in disk.

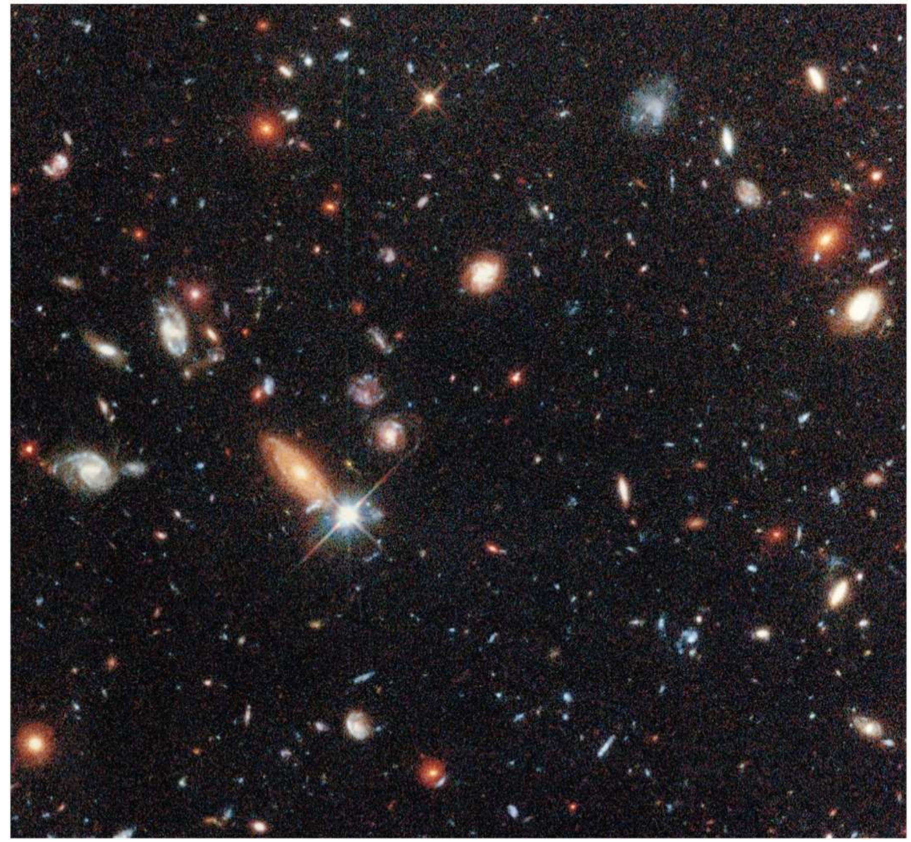
- Ellipticals
  - Star types: Only Pop II, blue stars rare.
  - Interstellar content: Very low density, very hot gas.

- Irregulars
  - Star types: blue stars common, indicating recent star formation.
  - Interstellar content: As much as 50% by mass.

- a: Courtesy of R. Jay GaBany-Collaboration: A. Sollima (IAC), A. Gil de Paz (U. Complutense Madrid) D. Mattinez-Delgado (IAC, MPIA), J.J. Gallego-Laborda (Fosca Nit Obs.), T. Hallas (Hallas Obs.)

Views of Distant Galaxies

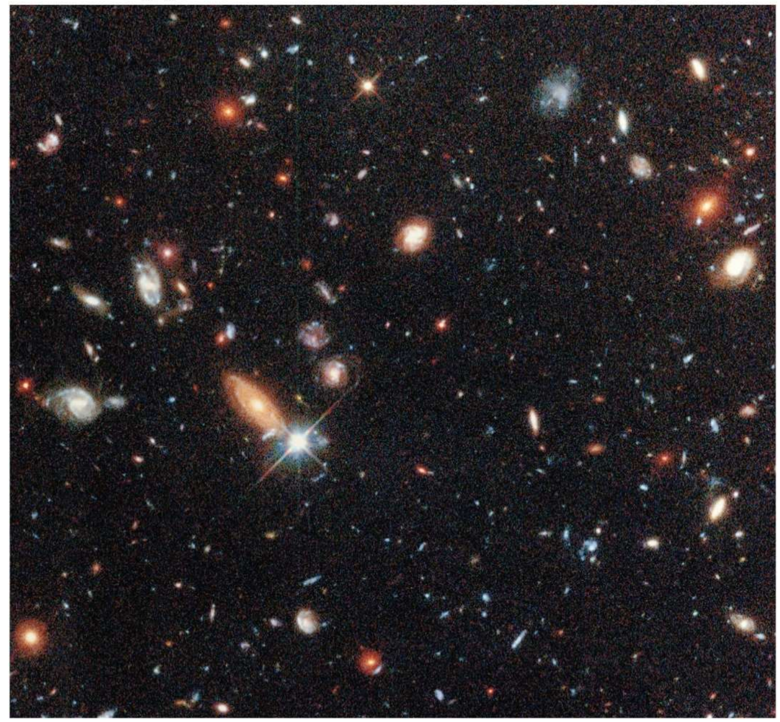
- Very distant clusters have a higher proportion of spirals than near clusters.
- Distant clusters contain more galaxies within a given volume.
- Galaxies are smaller than the Milky Way.



- NASA/JPL/STScl Hubble Deep Field Team

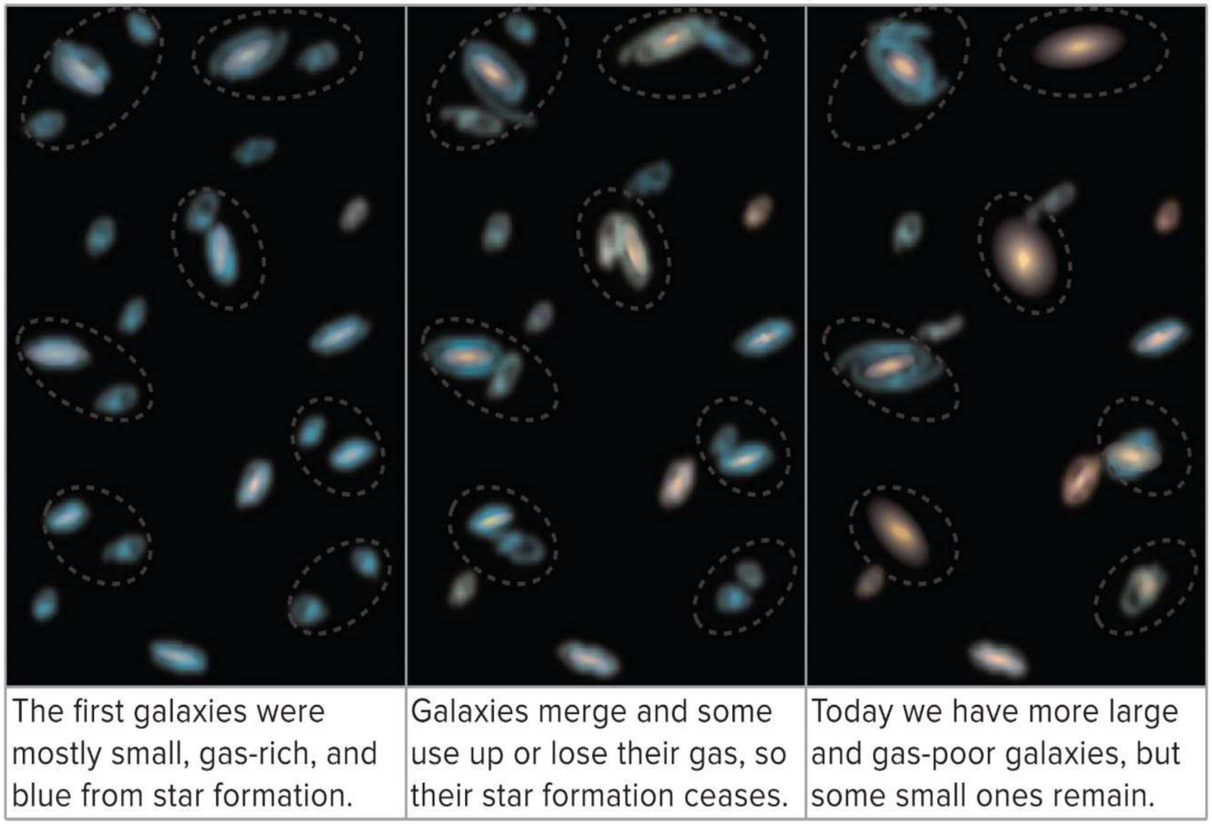
Galactic Interactions

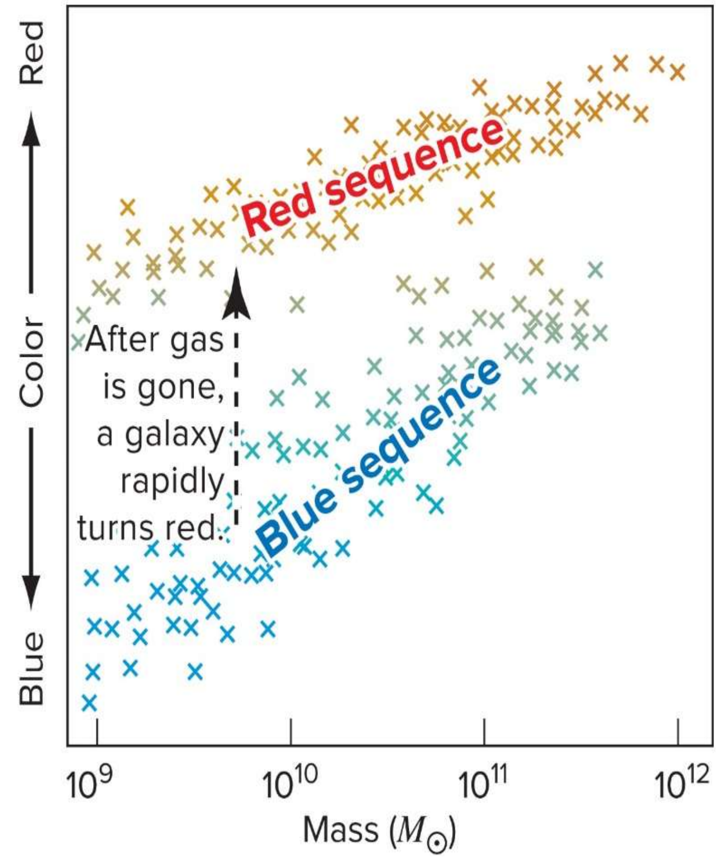
- Distant galaxies show more signs of disturbance by neighboring galaxies (odd shapes, bent arms, twisted disks), what astronomers call "harassment."



- NASA/JPL/STScI Hubble Deep Field Team

Galactic Evolution





Active Galaxies

- Centers (nuclei) emit abnormally large amounts of energy from a tiny region in their core.
- Emitted radiation usually fluctuates.
- In many instances intense radio emission and other activity exists well outside the galaxy.
- Centers of active galaxies referred to as AGNs – active galactic nuclei.
- 10% of all galaxies are active.
- Three overlapping classes: radio galaxies, Seyfert galaxies, and quasars.

Seyfert Galaxies

- Spiral galaxies (mostly) with abnormally luminous nucleus.
- As much energy output as the entire Milky Way.
- Region of emission is less than a light-year across.
- Wavelength emissions range from infrared to X-ray.
- Intensity fluctuates rapidly, sometimes changing in a few minutes.

- Hubble Heritage Team (AURA/STScI/NASA/ESA)

Seyfert and Radio Galaxies

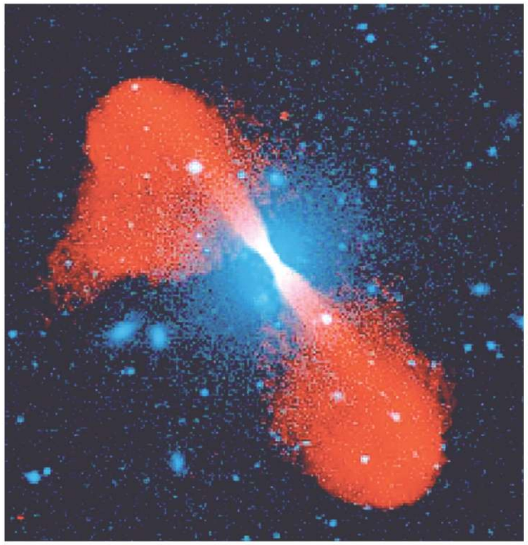
- Contain gas clouds moving at high speed.
- Occasionally the gas is ejected in small jets.

- Rapidly moving gas and small, bright nucleus make Seyfert galaxies similar to radio galaxies, and, in fact, some Seyfert galaxies are radio galaxies as well.

- Hubble Heritage Team (AURA/STScI/NASA/ESA)

Radio Galaxies

- Generally elliptical galaxies.
- Emit radio energy that comes from core and regions symmetrically located outside of galaxy.
- Outside regions are called “radio lobes” and span hundreds of millions of light-years.
- Core source is less than a light-month across.



A

- (a-c): NRAO/AUI/NSF

Jets and Lobes in Radio Galaxies

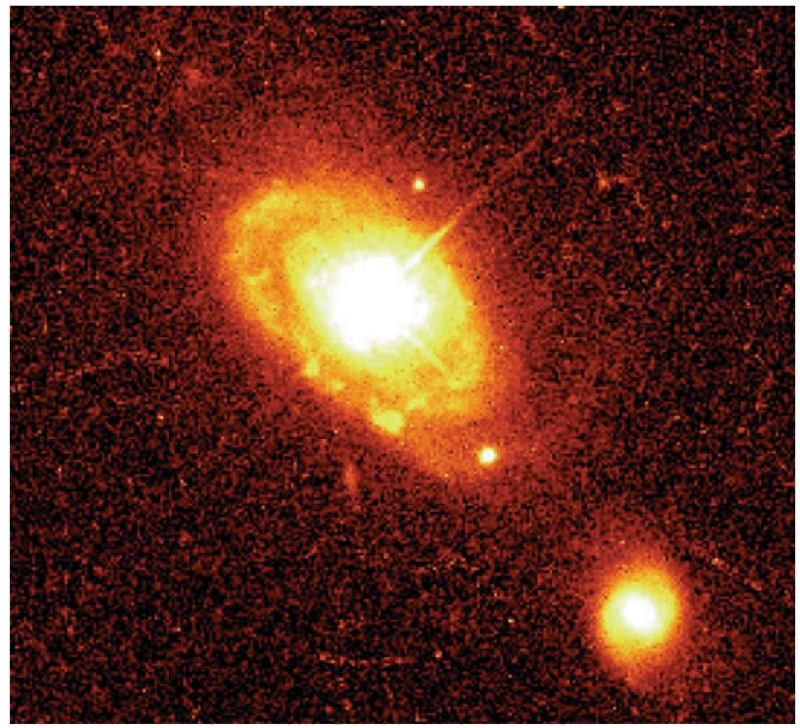
- Energy is as much as 1 million times more than normal galaxies.
- Radio emission is synchrotron radiation.
- High-speed electrons are generated in core and shot out via ***jets*** in general direction of the lobes.
- High-speed electrons eventually collide with surrounding gas and spread out to form lobes.

(left): NRAO/AUI/NSF; (right): L. Ferrarese (Johns Hopkins University)/NASA

- (left): NRAO/AUI/NSF; (right): L. Ferrarese (Johns Hopkins University)/NASA

Quasars

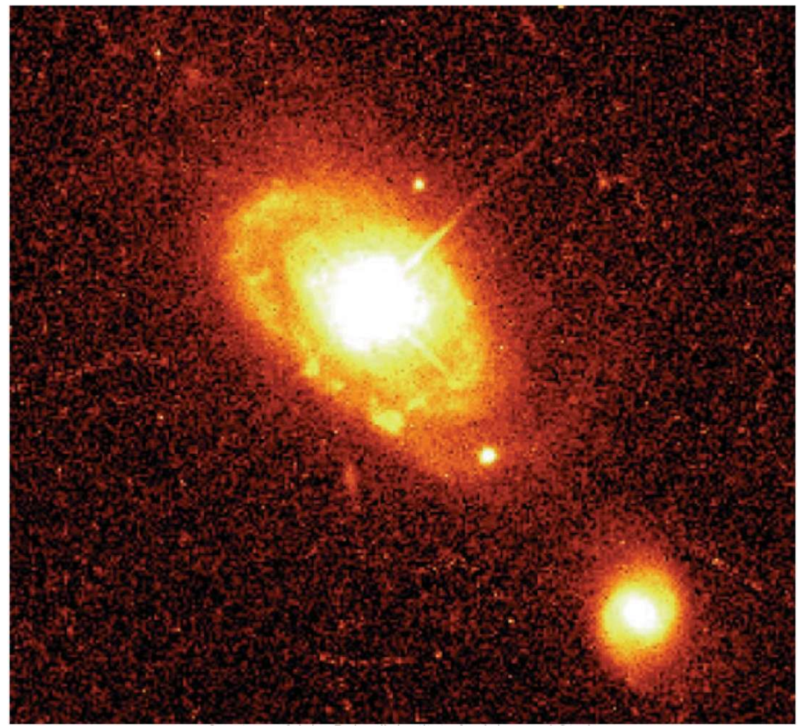
- Largest redshifts of any astronomical object.
- Hubble law implies they are at great distances (as much as 10 billion light-years away).
- To be visible at those distances, they must be about 1000× more luminous than the Milky Way.



- Courtesy of John Bahcall, Institute for Advanced Study

Quasars and other Active Galaxies

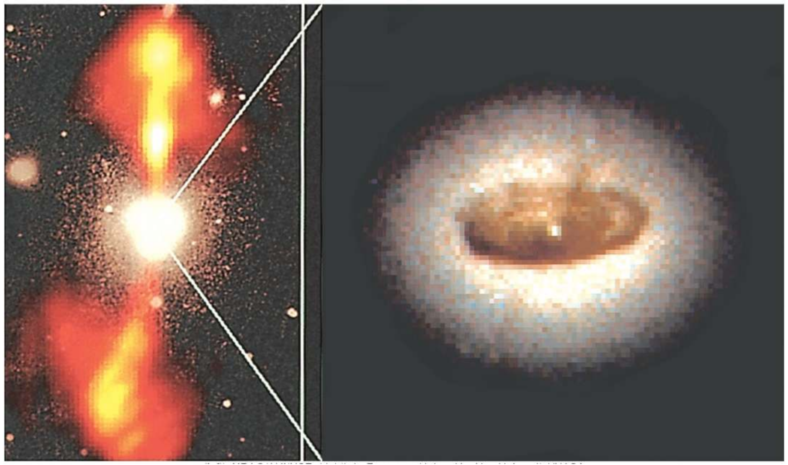
- Some similar to radio galaxies in emissions.
- Others similar to radio and Seyfert galaxies in that they eject hot gas from their centers.
- Apparent "superluminal" motion in jets indicate extreme high-speed motions.



- Courtesy of John Bahcall, Institute for Advanced Study

New Findings

- Recent images reveal quasars often lie in faint, fuzzy-looking objects that appear to be ordinary galaxies.
- Based on output fluctuations, quasars resemble the AGNs of radio galaxies and Seyfert galaxies in that they are small (fractions of a light-year in some cases).



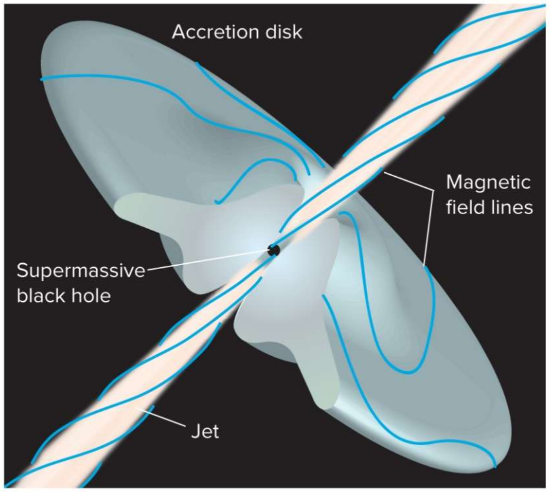
- (left): NRAO/AUI/NSF; (right): L. Ferrarese (Johns Hopkins University)/NASA

Cause of Activity in Galaxies

- All active galaxies have many features in common – this suggests a single model to explain all of them.
- Such a model must explain how a small region can emit an extreme amount of energy over a broad range of wavelengths.
- Model must be unusual since no ordinary star could be so luminous nor could enough ordinary stars be packed into such a small volume.

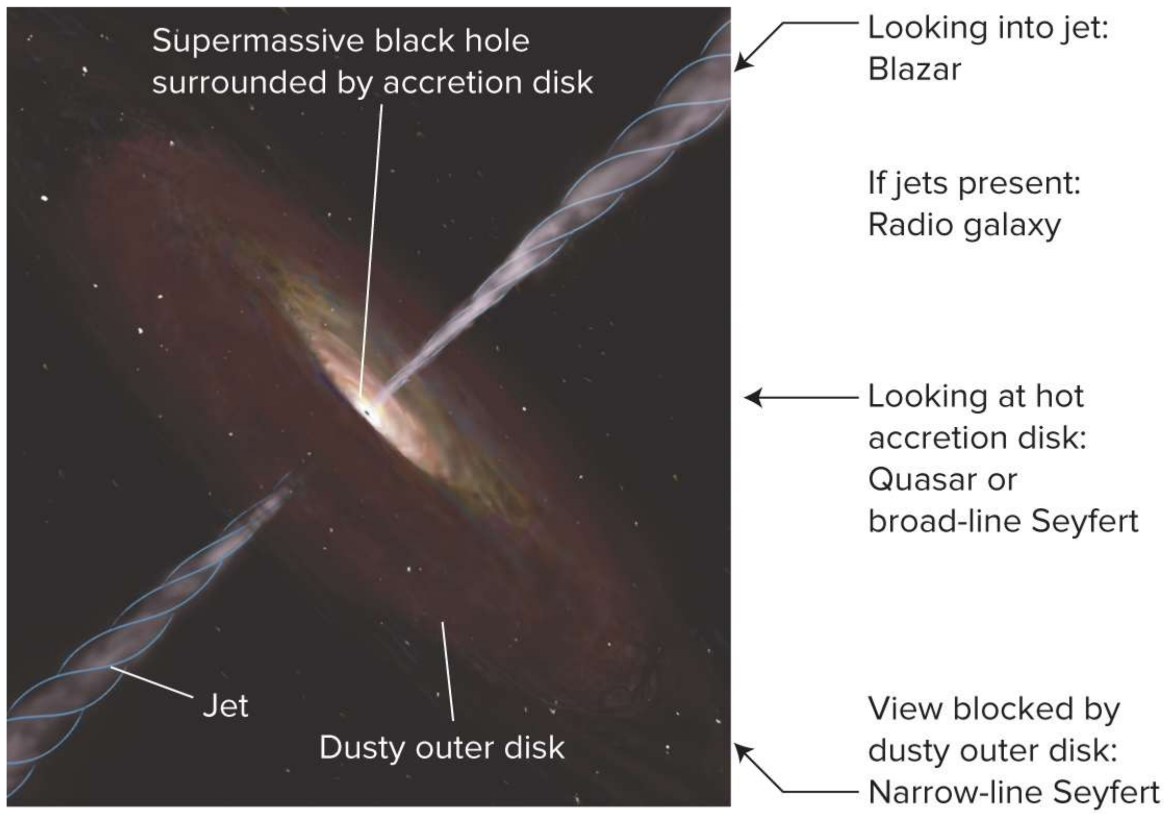
Basic Model of Activity

- Basic model:
- Black hole about the size of Earth with a gas accretion disc tens to hundreds of AU across.
- Most gas drawn into black hole heats to millions K.
- Some gas channeled by magnetic fields into jets.
- Accretion gas replenished by nearby passing stars or material from collision with another galaxy.



B

Different Views of an Active Galaxy



A

Massive Black Holes

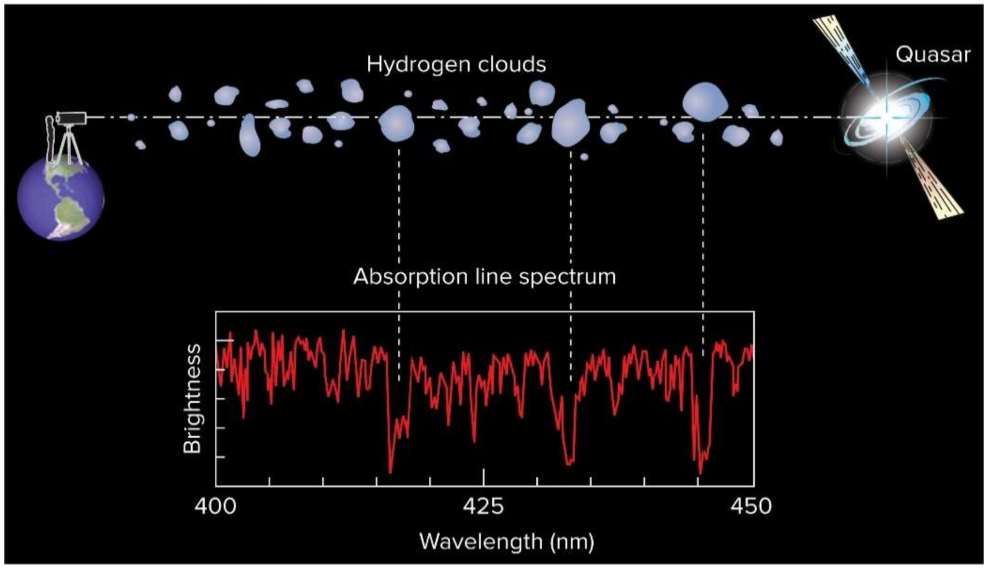
- Creation of massive black hole:
- Massive star in densely populated core of galaxy explodes forming a small black hole of ~5 $M_{¤}$.
- Black hole grows from accretion of interstellar matter.
- Radius of black hole increases making capture of more material easier.
- Eventually black hole becomes large enough to swallow entire stars.
- Growth of black hole is exponential until equilibrium with available materials stops growth.

Observational Proof

- Observational "proof" – extremely high speeds of gas and stars at very small distance from galactic center requires huge mass there (at least millions of solar masses), yet this mass emits no radiation of its own.
- All galaxies appear to have massive black holes at their centers.
- Not all galaxies are active, especially older ones, because central source of material to black hole is diminished.

Quasars as Probes of Intergalactic Space

- The immense distances of quasars allow their light to be used as probes of the intervening material.
- Quasar absorption lines have very different Doppler shifts from the emission lines of the quasars themselves – an indicator of cool gas clouds between the quasar and Earth.
- A quasar's light may be affected by a ***gravitational lens.***



Friday (5/15)

- C-Day

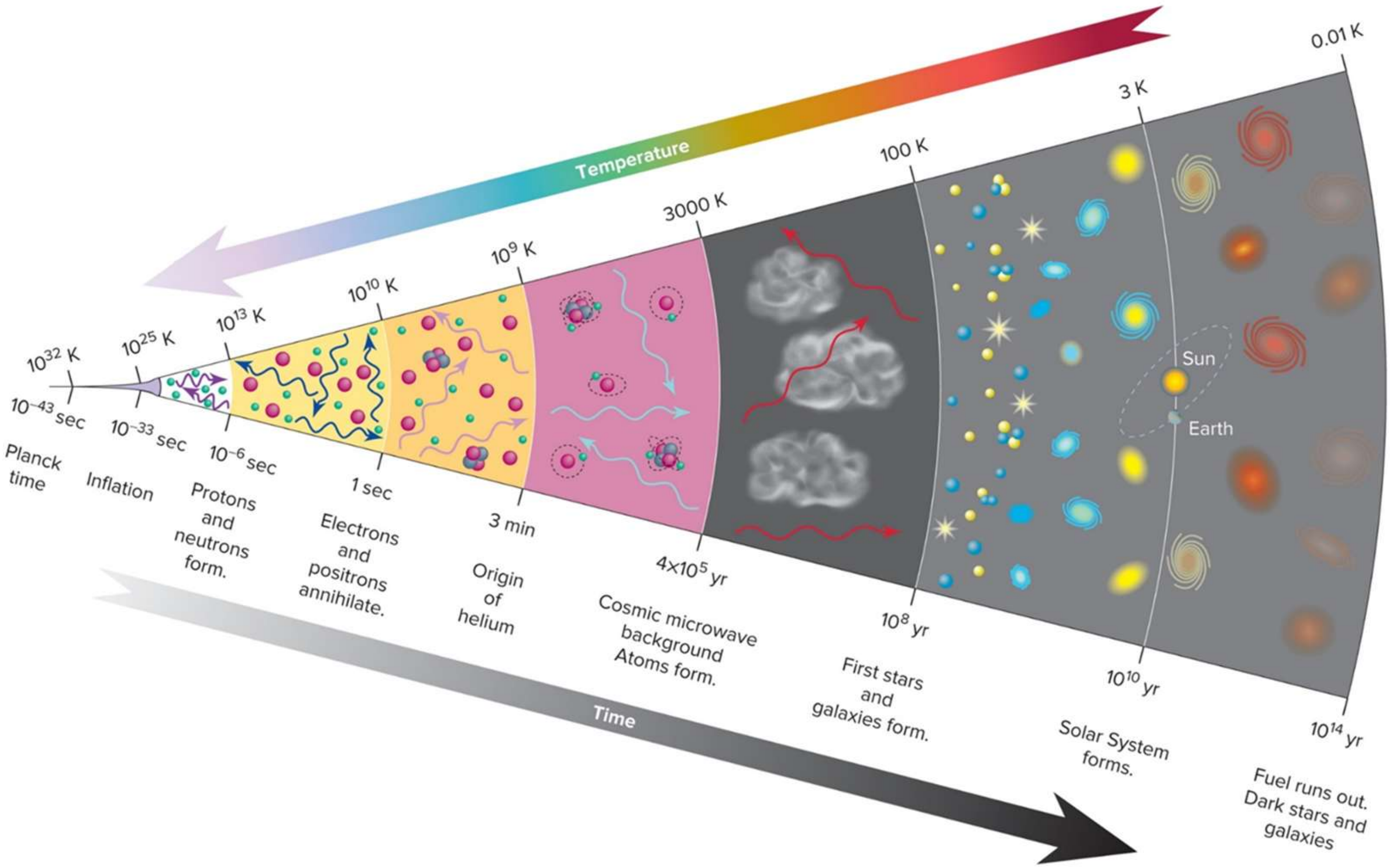
Monday / Tuesday (5/18 & 19)

T: **(15) Science concepts. The student knows the scientific theories of cosmology. The student is expected to:**

(A) describe and evaluate the historical development of evidence supporting the Big Bang Theory;

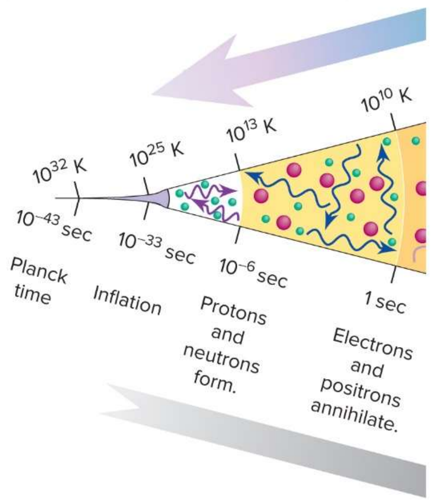
- O: I will explore the big bang theory
- D: by watching a video, participating in a lecture, and completing a reading assignment.
- A: big bang theory
- Y: How active was the universe at the beginning vs now?

History of the Universe



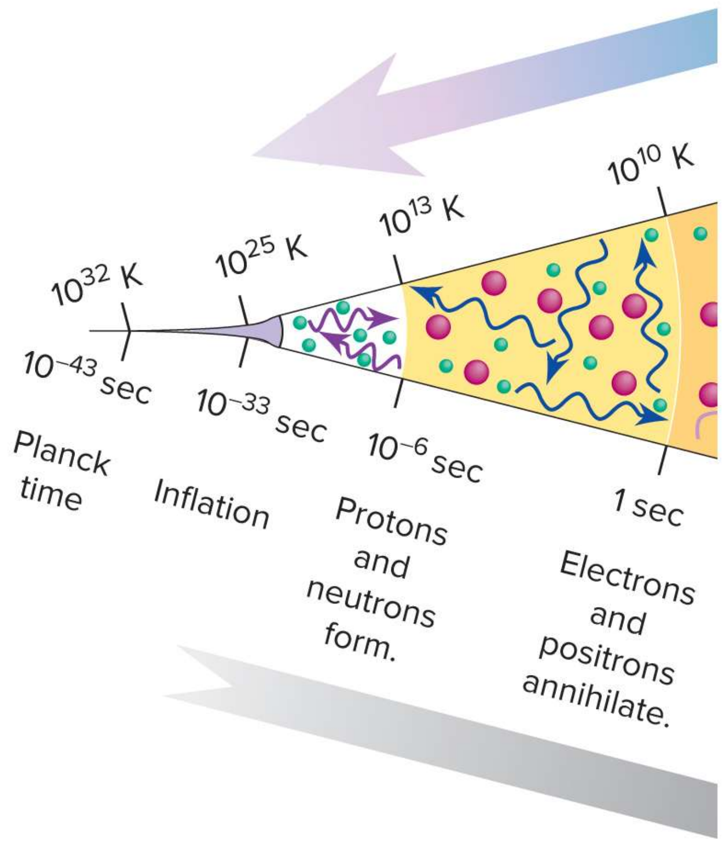
T-Plus 1 microsecond

- At one microsecond after the Big Bang
  - Temperature 10^{13} K, • hot enough for photons to create quarks and antiquarks.
  - Diameter smaller than Earth's orbit.
  - Universe expands at near speed of light and cools.
  - Lower temperature no longer produces quarks/antiquarks.
  - Subatomic physics dictates that existing quarks/antiquarks annihilate asymmetrically leaving an excess of quarks.
  - Surviving quarks combine into protons, neutrons.



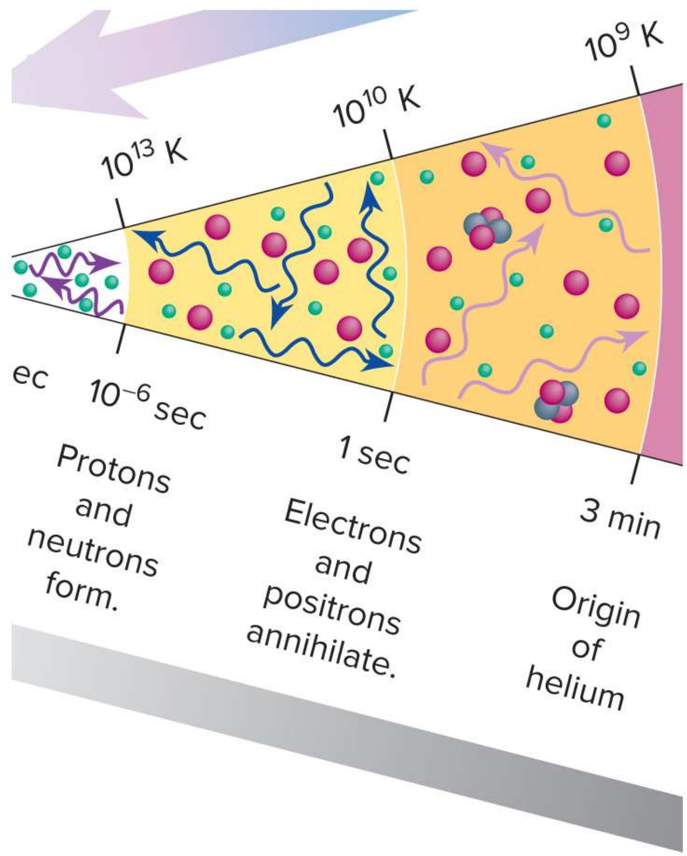
T-plus 5 seconds

- After 5 seconds or so, the Universe cools enough for the creation of matter to cease.



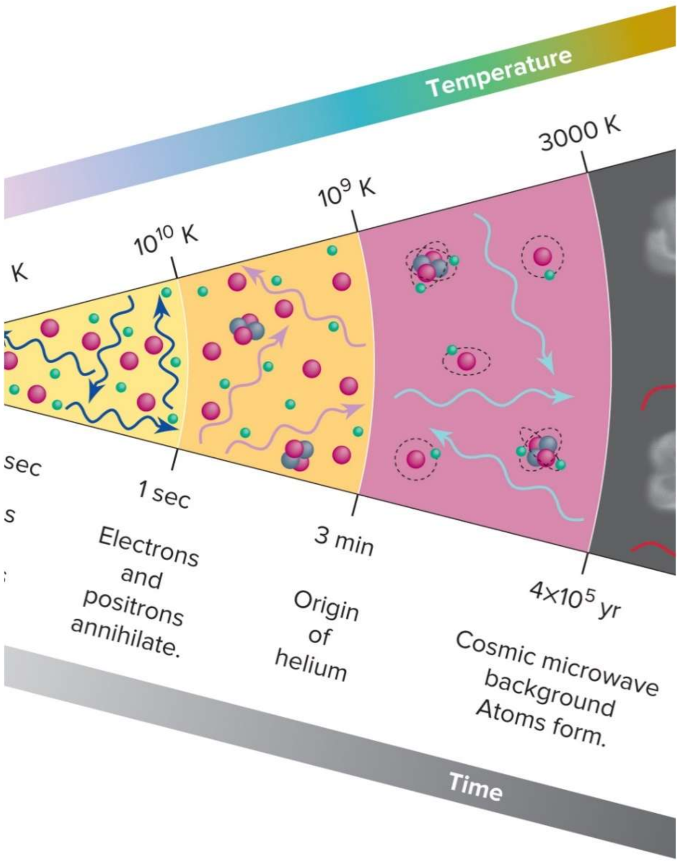
T-plus 3 minutes

- At 3 minutes after the Big Bang
  - Temperature is a few hundred million degrees.
  - ¼ of protons fuse into helium.



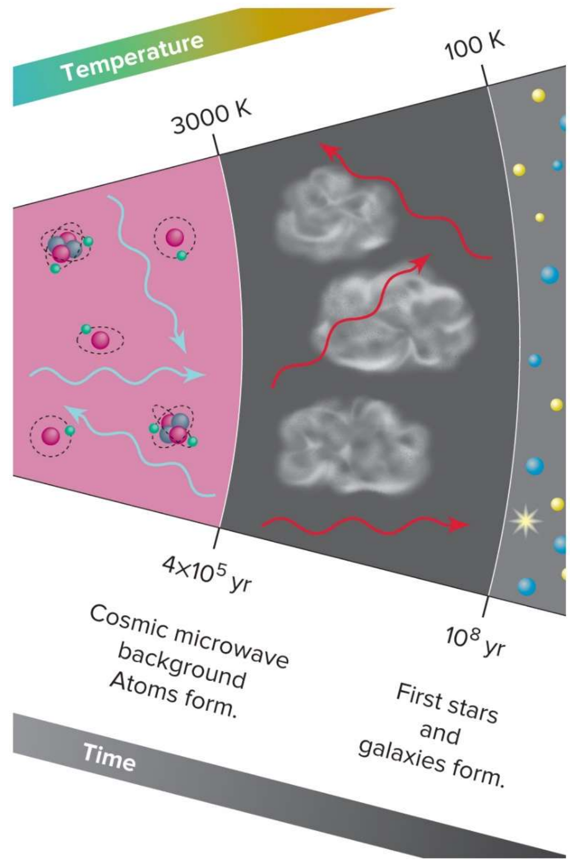
T-plus 500,000 years

- Next half million years
  - Further expansion and cooling.
  - Electrons begin to bind to protons to make hydrogen molecules (this is referred to as the recombination era).
  - At end of period, photons and matter go their separate ways.



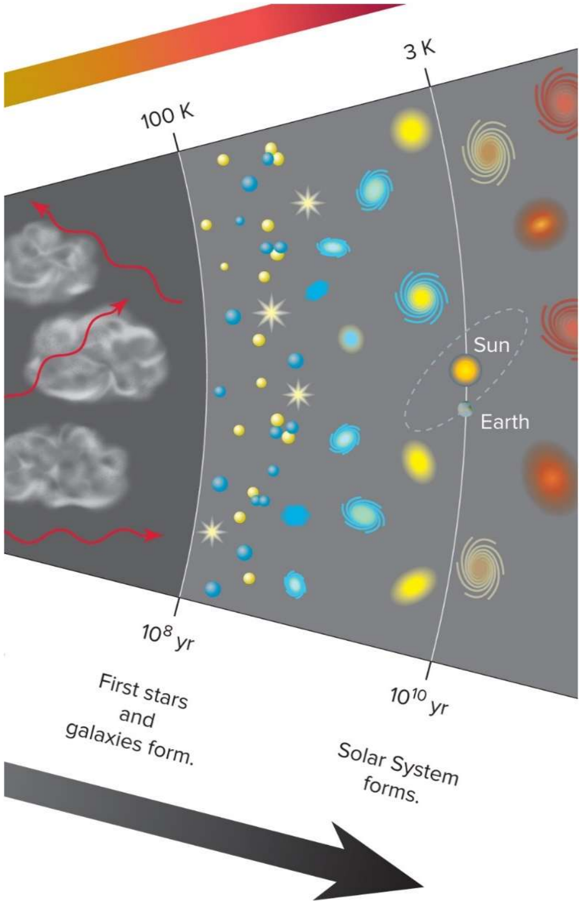
Protogalaxies

- Considering ages of several galaxies, galaxy formation had to start soon after recombination era.
- Protogalaxies formed from gravitational collapse of gas clouds.



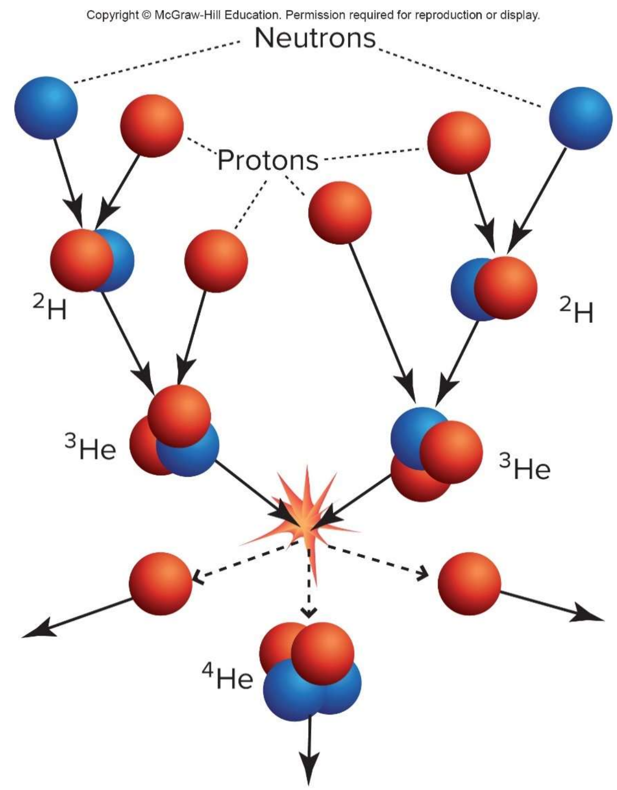
Formation of Galaxies

- Gravity too feeble to create galaxies in time scales needed.
- Need for dark matter to speed things up.
- Dark matter forms clumps around which the protogalaxies form.
  - Areas rich in dark matter clumps form large scale galaxy chains and sheets.
  - Area depleted in a dark matter form voids.



The Origin of the Elements

- Current theory suggests that the early Universe consisted of protons, neutrons, and electrons.
- The initial hot and dense state allowed nuclear reactions to create helium.
- Based on estimates of the early Universe's expansion rate, about 24% of the matter should be transformed to helium.
- Similar measurement of deuterium (^2H)
    - and lithium also support the hot,
    - dense early Universe idea.

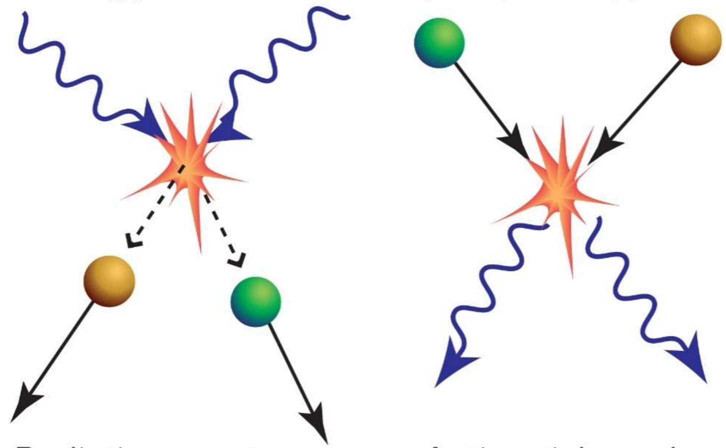


The Origin of the Universe

- The early Universe's high temperature and density imply that it may have had a very simple structure.
  - Mass and radiation mingled in a manner unlike their sharp distinction today.
  - Radiation is so energetic that it easily transforms to mass – mass and radiation behaved as a single entity.

Radiation, Matter, and Antimatter

- $E = mc^2$ tells us not only
- can mass be transformed to energy (as in stars), but that energy (in photons) can be transformed into mass.
  - The creation of mass, however, must come in pairs, ordinary matter, and ***antimatter.***
  - The antiparticle of the electron is the positron, the antiparticle of the proton is the antiproton.



Radiation creates particle and antiparticle.

A

Antiparticle and particle annihilate, creating radiation.

B

The (Very) Early Universe

- What was the state of the Universe at one microsecond?
  - The Universe had a temperature of about 10^{13} K.
  - the Universe we now see was packed into a volume smaller than the Solar System.
  - As space expanded, this dazzlingly hot matter (quarks and anti-quarks) and radiation cooled.
  - Protons and neutrons formed from quarks not annihilated by anti-quarks.

Wednesday (5/20)

- Field day for Freshmen in the AM and Sophomores in the PM

Thursday (5/21)

- Field Day for Seniors in the AM and Juniors in the PM.

Friday (May 22)

- C-day

Tuesday / Wednesday (May 26 & 27)

Thursday (May 28th)

- Why do we even have this day?