

# Lecture 4: Large-Scale Structure and Cosmology

## Galaxies and Dark Matter

A \_\_\_\_\_ is a gravitationally-bound collection of stars, gas, and dust, like our galaxy, the Milky Way

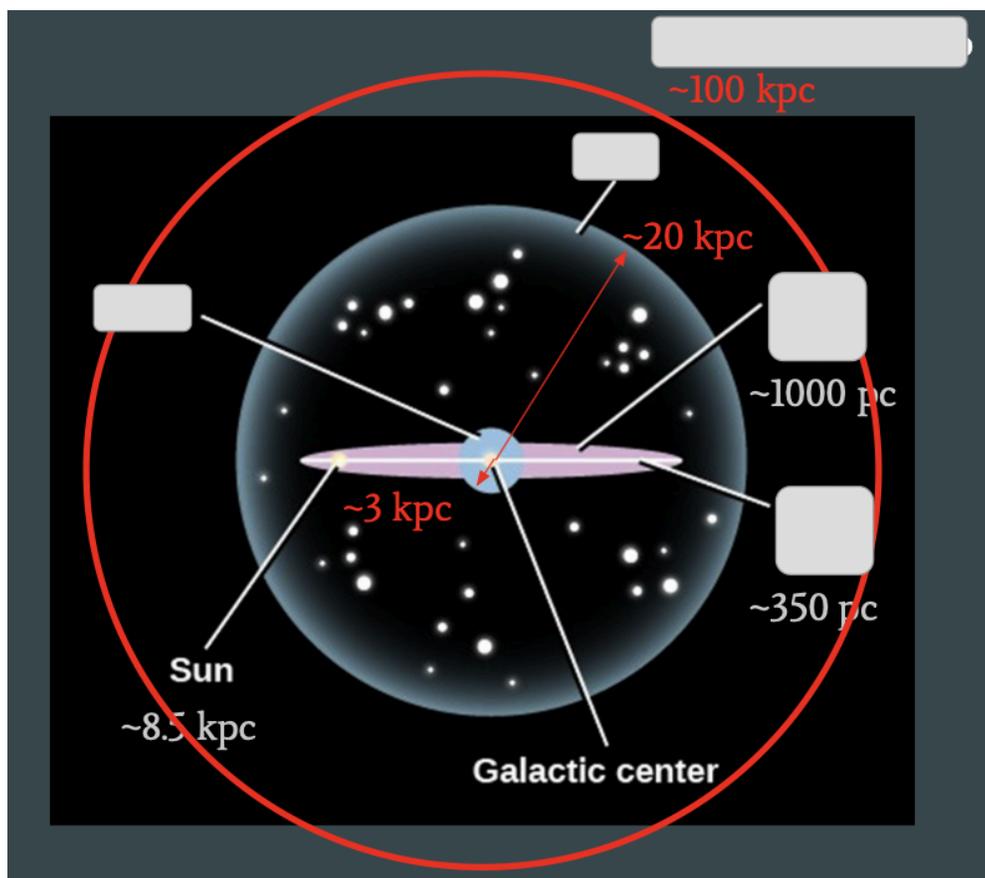
- Galaxy masses range from  $10^7 - 10^{13} M_{\odot}$ , with diameters from 1 – 100 kiloparsecs
- **Hubble Sequence** - morphological galaxy classifications
  - “Early type”: Dwarf, Elliptical, Lenticular galaxies **[NOT actually younger or older]**
  - “Late type”: Spiral, Irregular galaxies **[NOT actually younger or older]**
  - Subclasses are based on the **brightness** of bulge and disk, the \_\_\_\_\_ of **spiral arms**, and how well stars and HII emission nebulae are \_\_\_\_\_ in spiral arms



- \_\_\_\_\_ - gravitationally bound collection of 50 or less galaxies
  - The **Local Group** consists of the **Milky Way**, The Andromeda Galaxy (M31), and many orbiting \_\_\_\_\_ galaxies
- \_\_\_\_\_ - gravitationally bound collection of hundreds to thousands of galaxies
  - **Field galaxies** - galaxies not apparently bound to galaxy clusters

- \_\_\_\_\_ - largest known gravitationally bound structure in the universe, containing sub-clusters and superclusters
  - The **Local Group** is part of the **Virgo** supercluster, which is part of the **Laniakea Supercluster**
- **Luminosity function** - distribution of galaxy luminosities
  - Closely follows **Schechter function** for early (elliptical) galaxies
  - Deviates from **Schechter function** for late (spiral, irregular) galaxies; fewer low luminosity galaxies than expected

### Structure of the Milky Way



- **Population I stars:**
  - \_\_\_\_\_ stars formed from heavy elements ejected from the supernovae explosions of the first stars in the galaxy
  - Mostly found in \_\_\_\_\_, but can also be found in the bulge
- **Population II stars:**
  - \_\_\_\_\_ stars formed from primordial gas before the first stars exploded
  - Found in the **bulge** and **halo**

- **Population III stars** haven't been confirmed, but are theorized to form from primordial H and He shortly after Big Bang
  - **Star Formation History** - star formation rate as a function of Galaxy age; remains complex, population model insufficient
  - **Dark Matter** - non-luminous matter that makes up ~90% of the universe, found in the **dark matter halo** of galaxies based on the gravitational effects
  - Galaxy formation is still being explored, but most evidence suggests a \_\_\_\_\_ formation process:
    - [1] **The Cosmic Web** - Dark matter density perturbations ( $10^{12} M_{\odot}$ ) that define where galaxies will form
    - [2] Within DM perturbations, the first small clusters ( $10^6 M_{\odot}$ ) collapse, begin forming the galactic **bulge** stars and globular clusters
    - [3] Collisions between small clusters disrupt star formation, collide into larger ( $10^{10} M_{\odot}$ ) proto-galaxies that will become the **stellar halo**
    - [4] Residual torque from collisions and gravitational interactions induce angular momentum, causes matter to settle into the **thick disk**
    - [5] Cool gas settles into the **thin disk** at a smaller scale height
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## General and Special Relativity

In **Newtonian Relativity**, for an object moving at velocity  $\mathbf{v}$  in one frame, the apparent speed in a moving reference frame  $\mathbf{v}'$  is the **sum  $\mathbf{v}+\mathbf{v}'$** . But this breaks down when velocities approach the \_\_\_\_\_

### Special Relativity

- **Einstein's postulates of special relativity:**
  - **(1) principle of relativity:** the laws of physics apply in all **inertial** reference systems (reference frame is not accelerating)
  - **(2) the universal speed of light:** the speed of light in vacuum is the same for all inertial observers, regardless of the motion of the source
- **Lorentz factor:**  $\gamma = \frac{1}{\sqrt{1-(v^2/c^2)}}$

- \_\_\_\_\_: clocks in a moving reference frame measure a shorter time (run slow) than clocks in a rest frame:  $\Delta t' = \sqrt{1 - v^2/c^2} \Delta t$
- \_\_\_\_\_: length measured in a moving reference frame is shorter than length measured in rest frame:  $\Delta x' = \frac{1}{\sqrt{1-v^2/c^2}} \Delta x$
- **Relativity of simultaneity:** Events that happen at the same time in one reference frame are not necessarily simultaneous in another
- **Lorentz Transformation** - convert from coordinates (x,y,z, and t) in one inertial frame S to coordinates (x',y',z', and t') in frame S' moving at speed **v** relative to frame S
  - $ct' = \gamma(ct - \beta x)$
  - $x' = \gamma(x - \beta ct)$
  - $y' = y, z' = z$
- **Energy and momentum:**
  - Einstein redefines **relativistic** \_\_\_\_\_ redefined using the **proper velocity** (velocity measured as change in x divided by **proper time** elapsed in the rest frame):  $p = \frac{mv}{\sqrt{1-v^2/c^2}} = \gamma mv$
  - **Relativistic energy** is the 'time' component of relativistic momentum, multiplied by c:  $E = \frac{mc^2}{\sqrt{1-v^2/c^2}} = \gamma mc^2$
  - **Rest energy** is when  $\gamma = 1$ , resulting in Einstein's famous equation:  $E_{rest} = mc^2$
  - $E^2 = (pc)^2 + (mc^2)^2$
- **Synchrotron** radiation- requires charged particles to move near the speed of light; radiation is **relativistically beamed** in the direction of motion
- \_\_\_\_\_ motion- radio jets can appear to move faster than the speed of light due to **time dilation**

**General relativity** is a generalization of special relativity accounting for gravity in a \_\_\_\_\_ 4-dimensional \_\_\_\_\_ (x,y,z,t)

- (1) \_\_\_\_\_ tells \_\_\_\_\_ how to curve; \_\_\_\_\_ tells \_\_\_\_\_ how to move
  - **Geodesic** - shortest path between two points within given geometry
  - **Photons/light** will always follow the geodesic, and therefore curves around massive objects

- (2) **Equivalence principle**: gravitational mass and inertial mass are the same; motion under gravity is identical to motion in an accelerating reference frame
- **Gravitational \_\_\_\_\_** - light's wavelength increases (frequency decreases) when traveling away from a massive object, and decreases (frequency increases) when travelling towards a massive object:  $1 + z = \frac{v_{obs}}{v_0} = \frac{\lambda_0}{\lambda_{obs}} = \sqrt{1 - \frac{2GM}{r_0 c^2}}$
- **Gravitational \_\_\_\_\_** - time runs more slowly in curved spacetime:  $\frac{\Delta t_0}{\Delta t_{obs}} = \sqrt{1 - \frac{2GM}{r_0 c^2}}$
- **Black Holes** - mass is collapsed into a small radius such that the escape velocity equals the speed of light
  - **Schwarzschild radius**  $R_s = 2GM/c^2$  - minimum radius a given mass can occupy before becoming a black hole; also equals the radius of the **event horizon**
- **Gravitational lensing** - galaxies behind massive objects (black holes, other galaxies, DM overdensities) can be seen as light bends around the foreground object
- **Gravitational Waves** - ripples in spacetime due to the rapid motion of extremely dense objects like orbiting black holes and neutron stars in binaries
  - We detect gravitational waves using \_\_\_\_\_ **interferometry**; just like in radio interferometry, we cross-correlate the signals of two **in-phase/coherent** lasers travelling in perpendicular directions
  - When a gravitational wave hits the laser, spacetime is compressed in one direction but unchanged in the other, causing the lasers to become **out-of-phase**, so we observe a \_\_\_\_\_
  - The **Laser Interferometer Gravitational-Wave Observatory (LIGO)**, **Virgo Interferometer**, and **Kamioka Gravitational Wave Detector (KAGRA)** use laser interferometry to detect gravitational waves

## Hubble's Law and the Expanding Universe

Edwin Hubble observed that distant galaxies all had spectral lines that were \_\_\_\_\_ (Doppler shifted to longer wavelengths) due to their motion, meaning that they were travelling **away from us**.

- **Hubble's Law: more distant galaxies moving away faster:**  $v_r \approx cz \approx \frac{H_0}{c} D$  where  $H_0 \approx 70 \text{ km/s/Mpc}$  is \_\_\_\_\_
  - But they can't all be moving away from Earth because the universe is \_\_\_\_\_ - it has no preferred center or direction
  - Instead, all galaxies must be moving away from each other, and accelerating → **universe is \_\_\_\_\_**, causing the spectral lines to experience \_\_\_\_\_
- As we look at higher redshifts, we're looking \_\_\_\_\_ in time (because it takes longer for the light to reach us) when the universe was more compressed; the **Cosmic Microwave Background** is evidence that the universe is expanding from what once was a hot dense singularity
- Accelerating expansion implies the presence of \_\_\_\_\_ which drives the expansion, though its nature is unknown and it cannot be detected