Outline

- Our Milky Way Galaxy— 30 March
  - Parts of the Milky Way
    - Disk, bulge, halo, globular cluster system
  - Orbits
    - are circular in the disk
    - elongated in other parts
  - Gas, dust, and young stars are in the disk.
  - Formation of disk
    - Gas that formed disk stars was orbiting MW in a circle
  - Formation of halo (two methods)
    - Gas that formed halo stars was streaming toward MW.
    - Halo stars were in a little galaxy that got caught by MW.
  - Most of the mass of the Milky Way is dark matter
- Other Galaxies— 1 April
  - Our Milky Way has
    - Young stars, dust, & gas in disk. Circular orbits.
    - Old stars in halo. Elongated orbits
  - How are other galaxies different from the Wilky Way?
    - Type of star? Gas? Dust?
    - Orbits
    - Dark matter
  - How did M87, the central galaxy in the Virgo Cluster come to its present form?
  - History of galaxies
- Quasars & Active Galactic Nuclei— 4 April
  - Most big galaxies have a black hole in the nucleus.
  - In quasars, the nucleus is so bright that that the galaxy looks like a point.
  - Mass of the black hole
    - 3,000,000,000$M_\odot$ in M87
    - 3,000,000$M_\odot$ in Milky Way
  - Material can be ejected along the spin axis.
- Hubble's Law—6 April
  - Hubble's Law: More distant galaxies are moving away faster.
    - Speed = H × Distance
  - H's Law implies
    - Universe is expanding
    - Universe started with a Big Bang
    - Universe expands away from every galaxy.
- Hubble's Law—8 Apr
  - Doppler effect
  - Universe expands by the same factor that the wavelength of light expands
  - Simplicio's questions
    - Do all distances expand with the universe?
    - Why do some distances expand and some distances stay the same?
- Radiation from the Big Bang—11 April
  - Penzias & Wilson discover (1965) the temperature of the universe is 2.7K.
  - Big Bang emitted black-body radiation, which is now 2.7 K.
  - Wavelength of radiation expands with the universe.
  - At an earlier time, when universe was 1/200 of present size, temperature was hot enough to ignite paper.
  - Evidence that radiation is from the Big Bang, rather than from nearby sources:

        - "Radiation is … isotropic, unpolarized, and free from seasonal variations."
- When the Universe was 3 Minutes Old—13 Apr
    - What did the Cosmic Background Radiation, now a cool 2.7 K, do in the past?
        - It was hotter.
        - Its energy was greater.
        - Its mass density was greater. Light has mass because light has energy.
            - $E = m c^2$.
- Helium Formed When the Universe was 3 Minutes Old—15 Apr
    - Most of the helium is primordial. It formed when the universe was 3 minutes old
    - Follow the neutrons
        - (Number of neutrons):(No. protons) = 1/7 now
        - A proton can change into a neutron with an energy cost of 2 MeV.
        - A neutron can change into a proton with no energy cost.
        - n:p = 1:1 at 1 ms, when energy of radiation was 40 MeV, much higher than energy cost.
        - As universe cools, n:p drops, because energy cost becomes significant.
        - At 3 min, n:p = 1/7. Deuterium becomes stable. Neutrons get safely locked up in He.
        - Ratio n:p changes very slightly up to present.
    - Observations of 4He (and 3He, 7Li, 2H) agree with calculations using Big Bang & nuclear physics
- Weighing—18 Apr
    - Weighing the earth with a cannonball
    - Weighing the universe
    - Define density parameter Ω = PE/KE. For universe, $\Omega = 8\pi G \rho / H^2$.
    - Universe will expand forever if $\Omega \leq 1$.
- Weighing Earth, Sun, & Universe—20 Apr
    - To weigh the earth, time the fall of a ball.
    - To weigh the sun, time the orbit of a planet.
    - To weigh the universe, time the doubling of the size of the universe.
        - Same as measuring the brightness of a supernova that occurred when U was half its present size.
- Repulsive Gravity—22 Apr
    - Data on supernovae: distant supernova are faint, even for a universe with no mass.
    - Dark energy/ cosmological constant
        - In Einstein's General Relativity, mass and pressure both cause gravity. (For Newton, only mass causes gravity.)
        - Einstein in 1920s: My equations of gravity admit "cosmological constant" where pressure is negative and equal to mass
            - For cosmological constant/ dark energy, force of gravity is repulsive.
- Weighing the Universe with the Cosmic Background Radiation—25 Apr
    - Decoupling is when universe changed from ionized to neutral and opaque to transparent
        - CBR is snapshot of universe at 300,000yr.
    - Wilkinson Microwave Anisotropy Probe (WMAP) satellite measured fluctuations in CBR
        - Ripples show density fluctuations at scale of 300,000 lyr.
    - Angle subtended by "yardstick" => distance => weighing

- What is the Universe Made of? Take a fair spherical sample of universe with radius same as moon's orbit. Sample has
  - 3 oz of ordinary matter, 1 lb of dark matter, 3 lb of dark energy
  - Ordinary matter—protons, neutrons, electrons
    - Stars, gas, dust, planets, us
    - 4%
  - Dark matter—not detected except through gravity
    - 23%
  - Light
    - Mass density is small now. Dominant before universe was 1 Million years old
  - Cosmological constant or dark energy
    - Repulsive
    - 73%