Cosmology

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The outline of the course

- The observed Universe
- Sketchy Cosmology
- Brief "Course" of General Relativity and the Friedmann-Lemaître-Robertson-Walker (FLRW) Metric
- Cosmological Models
- Distances in cosmology
- Elementary Particles and Fundamental Interactions
- Thermodynamics of the Early Universe
- Thermal Relics from the Big Bang
- Dark Matter and Dark Energy
- Inflation
- CMB
- Baryogenesis

The Course Grading

- mid-term written test
- written exam
- oral exam

Recommended Texbooks

1. L. Bergström and A. Goobar, "Cosmology and Particle Astrophysics"
2. A. Liddle, "An Introduction to Modern Cosmology" ("Wprowadzenie do kosmologii współczesnej")
3. E. Kolb and M. Turner, "The Early Universe"
4. D.S. Gorbunov and V.A. Rubakov, "Introduction to the theory of the early universe: Hot big bang theory"

The observed Universe

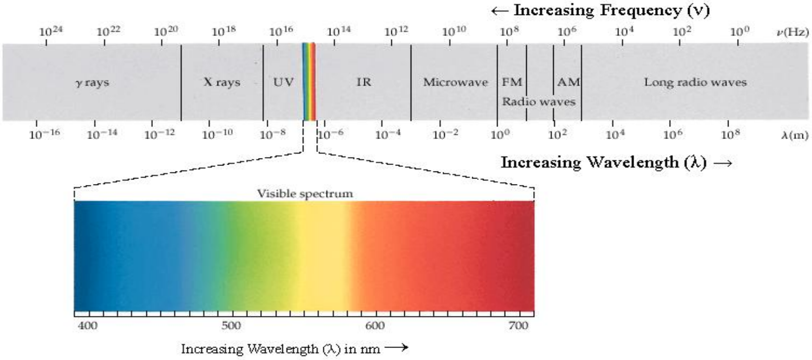

Figure 1: *The electromagnetic spectrum*

The observed Universe

- Gamma-Ray and X-Ray Astronomy:
  Gamma rays have the shortest wavelengths, $\lambda < 10$ pm = 10^{-11} m, which is less than the diameter of an atom. Special telescopes in orbit around Earth, such as the National Aeronautics and Space Administration's (NASA's) Compton Gamma-Ray Observatory, gather gamma rays before Earth's atmosphere absorbs them. X rays, the next shortest wavelengths (10 pm $< \lambda < 1$ nm), also must be observed from space.
- Ultraviolet Astronomy:
  Ultraviolet light has wavelengths larger than X rays, but shorter than visible light (1 nm $< \lambda < 100$ nm) . Ultraviolet telescopes are similar to visible-light telescopes in the way they gather light, but the atmosphere blocks most ultraviolet radiation. Most ultraviolet observations, therefore, must also take place in space. Most of the instruments on the Hubble Space Telescope (HST) are sensitive to ultraviolet radiation.

- Optional Astronomy:
  Professional astronomers today hardly ever actually look through telescopes. Instead, a telescope sends an object's light to a photographic plate or to an electronic light-sensitive computer chip called a charge-coupled device, or CCD. CCDs are about 50 times more sensitive than film. Telescopes may use either lenses or mirrors to gather visible light. The Hubble Space Telescope (HST) , a reflecting telescope that orbits Earth, has returned the clearest images of any optical telescope. The main mirror of the HST is only 94 in (2.4 m) across, far smaller than that of the largest ground-based reflecting telescopes. HST images of visible light are about five times finer than any produced by ground-based telescopes. Giant telescopes on Earth, however, collect much more light than the HST can. Often astronomers use space- and ground-based telescopes in conjunction.

- Infrared Astronomy:
  Infrared astronomers study parts of the infrared spectrum, which consists of electromagnetic waves with wavelengths ranging from just longer than visible light to 1000 times longer than visible light ($1\ \mu\text{m} < \lambda < 1$ mm). Earth's atmosphere absorbs infrared radiation, so astronomers must collect infrared radiation from places where the atmosphere is very thin, or from above the atmosphere. Most infrared wavelengths can be observed only from space. Every warm object emits some infrared radiation. Infrared astronomy is useful because objects that are not hot enough to emit visible or ultraviolet radiation may still emit infrared radiation. Infrared radiation also passes through interstellar and intergalactic gas and dust more easily than radiation with shorter wavelengths. Further, the brightest part of the spectrum from the farthest galaxies in the universe is shifted into the infrared.

- Microwave Astronomy:
  Planck was a space observatory operated by the European Space Agency (ESA) from 2009 to 2013. The mission substantially improved upon observations made by the NASA Wilkinson Microwave Anisotropy Probe (WMAP).
- Radio Astronomy:
  Radio waves have the longest wavelengths. Radio astronomers use giant dish antennas to collect and focus signals in the radio part of the spectrum. These celestial radio signals, often from hot bodies in space or from objects with strong magnetic fields, come through Earth's atmosphere to the ground. Radio waves penetrate dust clouds, allowing astronomers to see into the center of our galaxy and into the cocoons of dust that surround forming stars.

Other emissions:

- neutrinos:
  Most neutrino telescopes consist of huge underground tanks of liquid. These tanks capture a few of the many neutrinos that strike them, while the vast majority of neutrinos pass right through the tanks.
- cosmic rays:
  Cosmic rays are electrically charged particles that come to Earth from outer space at almost the speed of light. They are made up of electrons and protons. Astronomers do not know where most cosmic rays come from, but they use cosmic-ray detectors to study the particles. Cosmic-ray detectors are usually grids of wires that produce an electrical signal when a cosmic ray passes close to them.

- gravitational waves:
  Gravitational waves are a predicted consequence of the general theory of relativity. Various gravitational-wave observatories (detectors) are under construction or in operation, such as Advanced LIGO which began observations in September 2015 Potential sources of detectable gravitational waves include binary star systems composed of white dwarfs, neutron stars, and black holes. On February 11, 2016, the LIGO Scientific Collaboration and Virgo Collaboration teams announced that they had made the first observation of gravitational waves, originating from a pair of merging black holes using the Advanced LIGO detectors. A second detection of gravitational waves was announced on June 15, 2016.

- The astronomical unit:
  The astronomical unit (AU or au or a.u. or sometimes ua) is a unit of length approximately equal to the distance from the Earth to the Sun. The currently accepted value of the AU is
  1 AU = 149 597 870 700 m (nearly 150 million kilometers).

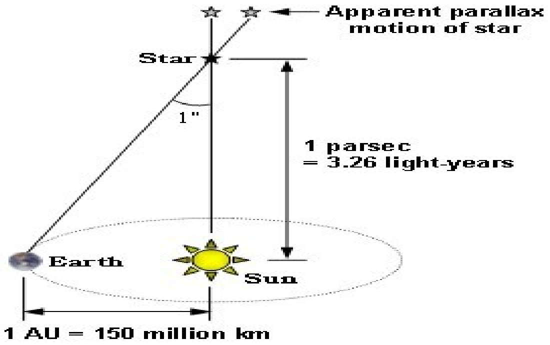

Figure 2: *The astronomical unit and the parsec*

- The parsec:
  The length of the parsec (pc) is based on the method of trigonometric parallax, one of the oldest methods for measuring the distances to stars. The name parsec stands for "parallax of one second of arc", and one parsec is defined to be the distance from the Earth to a star that has a parallax of 1 arcsecond. Parsec has been redefined in 2015 to exactly $648000/\pi$ astronomical units. The actual length is 1 pc $\simeq 206264.806247096$ AU, 1 pc $\simeq 3.085677581 \times 10^{16}$ m, or about 1 pc $\simeq 3.261563777$ ly. The nearest star, Proxima Centauri, is about 1.3 pc (4.2 light-years) from the Sun.
- Light-year:
  A light-year (symbol: ly) is a unit of length, specifically the distance that light travels in a vacuum in one year, 1 ly = 9.461×10^{15} m. While there is no authoritative decision on which year is used, the International Astronomical Union (IAU) recommends the Julian year (365.25 days).

Observed structures

- Stars:
  - Sun mass $M_\odot \simeq 2 \times 10^{30}$ kg
  - Distance to next closest stars (Alpha Centauri) $\simeq 4$ ly (1 ly $= 9.461 \times 10^{15}$ m)
- Galaxies:
  A galaxy (from the Greek root galaxias [$\gamma\alpha\lambda\alpha\xi\iota\alpha\zeta$], meaning "milky," a reference to the Milky Way) is a massive, gravitationally bound system consisting of stars, an interstellar medium of gas and dust, and dark matter. Typical galaxies range from dwarfs with as few as ten million (10^7) stars up to giants with one trillion (10^{12}) stars, all orbiting a common center of mass. There are probably more than 100 billion (10^{11}) galaxies in the observable universe. Most galaxies are 10^3 to 10^5 pc in diameter and are usually separated by distances of the order of millions of parsecs (or megaparsecs). Our Galaxy (Milky Way) has diameter $31 - 55$ kpc.
  - Spirals (e.g. Milky Way)
  - Ellipticals
  - Lenticular galaxies

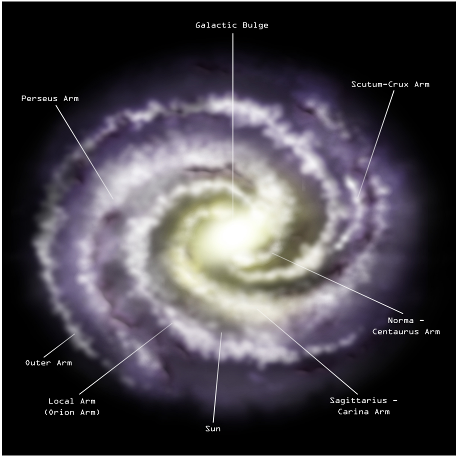

Figure 3: *Milky Way Galaxy, Face-on View*

The Milky Way is a spiral galaxy. It is the home of our Solar System together with at least 200 billion other stars (more recent estimates have given numbers around 400 billion). For mere details see: http://chandra.harvard.edu/resources/illustrations/milkyWay.html

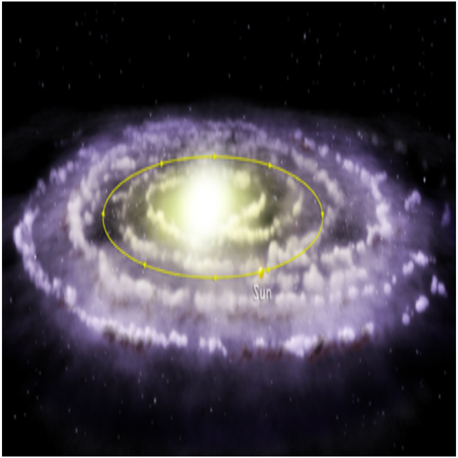

Figure 4: *Illustration of Solar System's Orbit*

It takes the Solar System (SS) about 225-250 million years to complete one orbit of the galaxy (a galactic year), so it has completed 2025 orbits during the lifetime of the Sun and 1/1250th of the galactic year since the origin of humans. The orbital speed of the Solar System around the center of the Galaxy is about 220 km/s, so it takes ~ 1400 years for the SS to travel a distance of 1 ly, or 8 days to travel 1 AU.

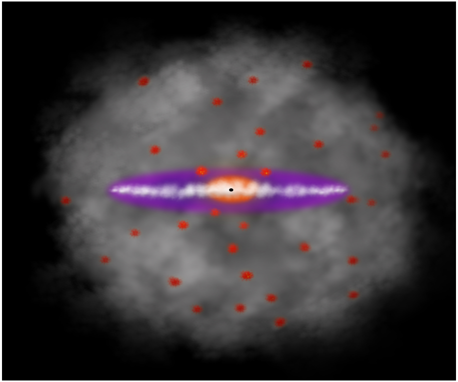

Figure 5: *Milky Way Halo*

Schematic view of Milky Way showing the DM halo (gray), globular clusters (a spherical collection of stars that orbits a galactic center as a satellite – red circles), the thick disk (old stars – dark purple), the stellar disk (white), the stellar bulge (tightly packed group of stars – red-orange), and the central black hole. The stellar disk is about 100 000 light years in diameter. The dark halo extends to a diameter of at least 600 000 ly.

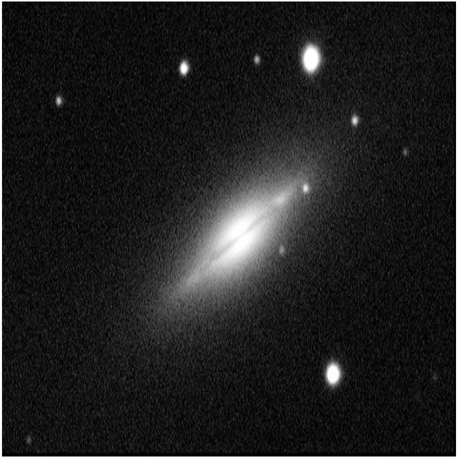

Figure 6: *Lenticular Galaxy M102*

A lenticular galaxy is a type of galaxy which is intermediate between an elliptical galaxy and a spiral galaxy. Lenticular galaxies are disc galaxies (like spiral galaxies) which have used up or lost their interstellar matter (like elliptical galaxies). Because of their ill-defined spiral arms, if they are inclined face-on it is often difficult to distinguish between them and elliptical galaxies.

Figure 7: *Elliptical Galaxy M87 (NGC 4486), type E1*

Elliptical galaxies have smooth, featureless light-profiles and range in shape from nearly spherical to highly flattened, and in size from hundreds of millions to over one trillion (10^{12}) stars. In the outer regions, many stars are grouped into globular clusters. Most elliptical galaxies are composed of older, low-mass stars, with a sparse interstellar medium and minimal star formation activity. Elliptical galaxies are believed to make up approximately 10-15 % of galaxies in the local Universe.

Figure 8: *Irregular Galaxy LMC, the Large Magellanic Cloud*

- Clusters of Galaxies:
  Their mutual gravity can draw galaxies together into clusters that are of the order of 10^6 pc across. Some clusters have only a handful of galaxies and are called poor clusters. Other clusters with hundreds to thousands of galaxies are called rich clusters. The low mass of a poor cluster prevents the cluster from holding onto its members tightly. The poor cluster tends to be a bit more irregular in shape than a rich cluster. Our Milky Way is part of a poor cluster called the Local Group. The Local Group has two large spirals, one small spiral, two ellipticals, at least 19 irregulars, at least 17 dwarf ellipticals and at least 5 dwarf spheroidals. There may be more irregular and dwarf galaxies. The Local Group is about 10^6 pc across with the two large spirals, the Milky Way and Andromeda Galaxy, dominating the two ends. Each large spiral has several smaller galaxies orbiting them. The proportions of the different types of galaxies in the Local Group probably represents the number of the different types of galaxies in the rest of the universe.

- Superclusters of Galaxies:
  Galaxy clusters attract each other to produce superclusters of tens to hundreds of clusters. Their mutual gravity binds them together into long filaments (thin, stringlike structures) 100 to 300 million pc long, and 5 to 10 million pc thick on average.
- Voids, sheets & filaments:
  Deep redshift surveys reveal a very bubbly structure to the universe with galaxies primarily confined to sheets and filaments. Voids are the dominant feature and have a typical diameter of about 25Mpc. They fill about 90% of space and the largest observed, Bootes void, has a diameter of about 124Mpc. Other features that have been observed are the ‘Great Wall’, an apparent sheet of galaxies 100Mpc long at a distance of about 100Mpc.

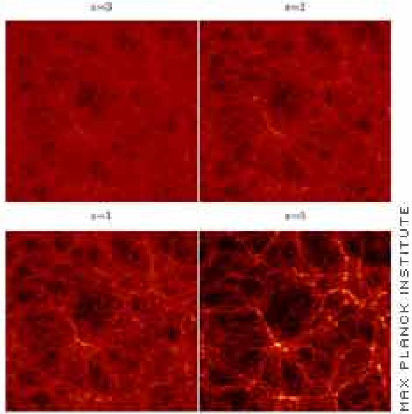

Figure 9: *The history of the Universe.*

History of the universe is being computer simulated. Matter condenses gradually (from top left to bottom right) out of a near-uniform soup. Each square represents a slice of the universe 550 million light-years on a side. Bright spots indicate regions of greater density of matter.

Synergy of X-ray and optical observations!

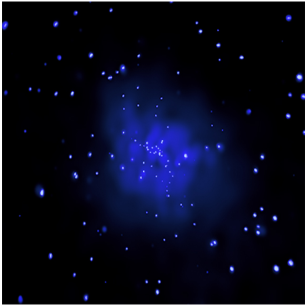

Figure 10: *Chandra X-ray Image of Andromeda Galaxy (M31)*

Figure 11: *Optical Image of Andromeda Galaxy (M31)*

Synergy of infrared and optical observations!

Figure 12: *The Sombrero Galaxy in Infrared*

This floating ring is the size of a galaxy. It is part of Sombrero Galaxy (M104), one of the largest galaxies in the nearby Virgo Cluster of Galaxies. The dark band of dust that obscures the mid-section of the Sombrero Galaxy in optical light actually glows brightly in infrared light. The above image shows the infrared glow, recently recorded by the orbiting Spitzer Space Telescope, superposed in false-color on an existing image taken by NASA's Hubble Space Telescope in optical light.