GALAXIES AND COSMOLOGY

The APM Galaxy survey
Maddox Sutherland Efstathiou & Loveday
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.
• 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)
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 2/3 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.

Correcting for dust effects and variable star types, astronomers conclude the disc has a 30 kpc diameter with the Sun 2/3 from the center (8-8.5 kpc).
Structure and Contents of the Milky Way

• 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
- Differential rotation with all objects circling in the same direction: 240 million-year period at 220 km/sec at the Sun’s orbit

**Spiral arms** distribution of stars, gas, and dust and the plane tilted with respect to Earth’s orbit around Sun about 60 deg
Structure and Contents of the Milky Way

• **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 1/3 the diameter of the galaxy
Age of the Milky Way

• Using stellar aging techniques, astronomers had estimated the galaxy’s most ancient stars to be about 15 billion years old

• More recent model calculations and observations suggests the old star ages are more like 13 billion years

• A rough estimate of the Milky Way then is about 13 billion years
Stars of the Milky Way

- From its rotation and effects on nearby galaxies, mass of Milky Way is $2 \times 10^{12}$ $M_\odot$
- Dividing the number of stars in the Milky Way by its age gives a star creation rate of 7-8 stars per year
- Most numerous stars turn out to be dim, cool, red dwarfs (mass about $0.5$ $M_\odot$)
- The average mass for Milky Way stars is $\sim 1$ $M_\odot$
- Stars more massive than $100$ $M_\odot$ are rare
- 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)
Two Stellar Populations

- **Population I**
  - Age: generally young (10⁶ to a few times 10⁹) years
  - Color: blue (generally)
  - Location: disk and concentrated in arms
  - Orbit: approximately circular in disk
  - Heavy-element content: high (similar to Sun)
Two Stellar Populations

- **Population II**
  - Age: old (about $10^{10}$ years)
  - Color: red
  - Location: halo and bulge
  - Orbit: plunging through disk
  - Heavy-element content: low ($10^{-2}$ to $10^{-3}$ Sun)
Gas and Dust in the Milky Way

**Interstellar matter**

- Interstellar clouds seen directly or detected by their effect on light from distant stars
  - Gas and dust imprint narrow absorption lines on starlight passing through interstellar clouds: such lines can give cloud’s composition, temperature, density, and speed
  - Dust is µm to nm in size, made of silicates and carbon compounds, and perhaps coated with ices of water, carbon monoxide, and methyl alcohol

- Gas found to be 71% H, 27% He, 2% heavy elements
Scattering

- This scattering is most effective when the light’s wavelength is smaller than the dust grain.
- The optimum scattering for interstellar dust and molecules in the Earth’s atmosphere is for blue and ultraviolet light.

The loss of blue light from a star due to scattering in an intervening cloud is called **reddening**.
• The large amount of dust in the galactic plane reduces almost to zero the number of distant galaxies that can be seen – this region of the sky is called the **zone of avoidance** (the galaxies can still be “seen” in the radio and infrared)
Mapping the Milky Way

• Most interstellar gas clouds are too remote from hot stars to be seen in the visible
  – We detect these clouds by measuring their radio output
  – For hydrogen, the \textit{21-centimeter radiation} is the radio emission that comes from the “spin flip” of the bound electron
Mass of the Milky Way

- A more refined technique uses the rotation speeds of stars at a variety of distances from the center (the so-called rotation curve).
- This technique can more accurately determine the mass of the entire galaxy – the Sun method only estimates the mass interior to its orbit.
Formation of the Milky Way

A few million ly

Some stars form.

Massive stars undergo supernova explosions.

~100,000 ly

Halo stars

Slowly rotating pregalactic cloud of pure hydrogen and helium begins to collapse under its own gravity.

Stars continue to form in collapsing cloud; supernovas add heavy elements to gas that begins settling into disk.

Disk stars

Stars form in disk; higher-mass stars in halo die, leaving only low-mass red stars behind.
Galaxies

• Beyond the Milky Way are billions of other galaxies
• Some galaxies are spiral like the Milky Way while others are egg-shaped or completely irregular in appearance
• Besides shape, galaxies vary greatly in the star, gas, and dust content and some are more “active” than others
• Galaxies tend to cluster together and these clusters appear to be separating from each other, caught up in a Universe that is expanding
Galaxies

• A galaxy is an immense and relatively isolated cloud of hundreds of millions to hundreds of billions of stars, and vast clouds of interstellar gas

• Each star moves in its own orbit guided by the gravity generated by other stars in the galaxy
Types of Galaxies

• By the 1920s, Edwin Hubble demonstrated that galaxies could be divided on the basis of their shape into three types, and two sub-types
Spiral Galaxies

- Two or more arms winding out from center
- Classified with letter S followed by a letter (a-d) to distinguish how large the nucleus is and/or how wound up the arms are
Barred Spirals

- Arms emerge from ends of elongated central region or bar rather than core of galaxy
- Classified with letters SB followed by the letters (a-d)
- Thought by Hubble to be a separate class of object from normal S spirals, computer simulations show bar may be result of a close encounter between two galaxies
- The Milky Way is accepted to be an SB galaxy
S0 Galaxies

- Disk systems with no evidence of arms
- Thought by Hubble to be intermediate between S and E galaxies, several theories now explain their appearance (e.g., an S0 lacks gas to produce O and B stars to light up any spiral arms that may exist)
Elliptical Galaxies

- Smooth and featureless appearance and a generally elliptical shape
- Classified with letter E followed by a number (0-7) to express “flatness” of elliptical shape
Irregular Galaxies

- Neither arms or uniform appearance - generally, stars and gas clouds scattered in random patches
- Classified as Irr
- Starburst Galaxies
Stellar and Gas Content of Galaxies

- Ellipticals have a large range of sizes from globular cluster sizes to 100 times the mass of the Milky Way
- Galaxies nearby Milky Way: Most are dim dwarf E and dwarf Irr sparsely populated with stars
- Distant galaxies: In clusters, ~60% of members are spirals and S0, while in sparsely populated regions it is ~80%
- Early (very young) galaxies are much smaller than Milky Way – merging of these small galaxies is thought to have resulted in the larger galaxies of today
The Cause of Galaxy Types

- Computer simulations show galaxies formed from gas clouds with large random motions becoming ellipticals, whereas small random motions become spirals.
- Ellipticals had a high star formation rate in a brief period after their birth, while spirals produce stars over a longer period.
- Dark matter halo spin rate – fast for spirals, slow for ellipticals.
- Density wave or Secondary Star Formation model for creating spiral arms.
Early Observations of Galaxies

• Since galaxies are so far away, only a few can be seen without the aid of a telescope: Andromeda and the Large and Small Magellanic Clouds

• In 18th century, Charles Messier cataloged several “fuzzy” objects to be avoided in comet searches – many turned out to be galaxies (M31 = Andromeda)
Early Observations of Galaxies

- In 19th century, William Herschel and others systematically mapped the heavens creating the New General Catalog (NGC) which included many galaxies (M82 = NGC 3034)
• Hubble proposed the “tuning fork” diagram as a hypothesis for galactic evolution – today it is believed this interpretation is incorrect. However, we still use his classification scheme.
Stellar and Gas Content of Galaxies

- **Spirals**
  - Star types: Mix of Pop I and Pop II
  - 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
  - Interstellar content: As much as 50% by mass
Galactic Collisions and Mergers

- Could galaxy’s type change with time?
  - Computer simulations show a galaxy’s shape can change dramatically during a close encounter with another galaxy
Consequences of a Collision

- Individual stars are left unharmed
- Gas/dust clouds collide triggering a burst of star formation
- A small galaxy may alter the stellar orbits of a large spiral to create a “ring galaxy”
- Evidence (faint shell-like rings and dense clumps of stars) of spirals colliding and merging into ellipticals. Happens most evidently in clusters.
Galaxy Distances

- Galaxy distances are too far to employ the parallax technique.
- The method of “standard candles” is used.
- The standard candles are usually Cepheid variables, supergiant stars, planetary nebulas, supernovas, etc.
- Tully-Fisher Method – The higher the rotational speed of a galaxy, the more luminous it is:  $$M = A - b n; \quad n = \log(2v) - 2.5$$
The Hubble Law

- In 1911, it was discovered that all galaxies (with but a few exceptions) were moving away from the Milky Way.
- Edwin Hubble found that these radial speeds, calculated by a Doppler shift analysis and called a *recessional velocity*, increased with a galaxy’s distance.
The Hubble Law

- From a plot of several galaxies’ known recessional velocities \( V \) and distances \( D \), Edwin Hubble, in 1920, discovered a simple formula:
\[
V = H \times D
\]

- Today, this expression is called the **Hubble law** and \( H \) is called the **Hubble constant**
The Hubble Law

• Although not completely agreed upon, $H$ is about $67.80 \pm 0.77$ km/sec/Mpc (Planck Mission--2013)

• With $H$ known, one can turn this around and determine a galaxy’s unknown distance by measuring its recessional velocity and assuming a value for $H$
Galactic Evolution

The first galaxies were mostly small, gas-rich, and blue from star-formation. Galaxies merge and some use up or lose their gas, so star-formation ceases. Today we have more large and gas-poor galaxies, but some small ones remain.
Measuring the Mass of Galaxies

- The mass of a galaxy is determined from the modified form of Kepler’s third law
- To use this method, one concentrates on some stars or gas on the outer fringes of the galaxy
- The semimajor axis distance used in Kepler’s third law is simply half the galaxy’s pre-determined diameter
- For the orbital period used in the third law, one uses Doppler analysis of the galaxy’s spectral lines to determine orbital speed and this speed used with the galaxy’s diameter gives the period
Dark Matter

- *Dark matter* is the material predicted to account for the discrepancy between the mass of a galaxy as found from the modified Kepler’s third law and the mass observed in the form of gas and dust.
Dark Matter

- The amount of matter needed to resolve this discrepancy is as much as $10 \times$ the visible mass.
- The strongest evidence that dark matter exists comes from galaxy rotation curves, which do not show diminishing speeds at large distances from the galaxy’s center.


**Particles in the Universe**

Universe contains fundamental particles and its behavior as a whole depends on the properties of these particles. One important question is if these particles are moving at relativistic speeds.

\[ E^2 = m^2c^4 + p^2c^2 \]

Non-relativistic--- mass-energy dominates

\[ E = mc^2 + \frac{p^2}{2m} \] where \( mc^2 \) is the rest mass-energy

Attributed to the Einstein's famous formula, a particle of zero rest mass moves with relativistic speeds near speed of light-- light itself, photon

**BARYONS**

A baryon is a composite subatomic particle made up of three quarks (as distinct from mesons, which comprise one quark and one antiquark). Baryons and mesons belong to the hadron family, which are the quark-based particles.

As quark-based particles, baryons participate in the strong interaction, whereas leptons, which are not quark-based, do not. The most familiar baryons are the protons and neutrons that make up most of the mass of the visible matter in the universe. Electrons (the other major component of the atom) are leptons.
Neutrinos are subatomic particles produced by the decay of radioactive elements and are elementary particles that lack an electric charge. There are three types of neutrinos: $\nu_e$, electron neutrino, $\nu_\tau$, Tau neutrino, and $\nu_\mu$, muon neutrino.

Copiously produced in high-energy collisions, travelling essentially at the speed of light, and unaffected by magnetic fields, neutrinos meet the basic requirements for astronomy. Their unique advantage arises from a fundamental property: they are affected only by the weakest of nature's forces and are therefore essentially unabsorbed as they travel cosmological distances between their origin and us.

A majority of the neutrinos were born around 15 billions years ago, soon after the birth of the universe. Since this time, the universe has continuously expanded and cooled, and neutrinos have just kept on going. Theoretically, there are now so many neutrinos that they constitute a cosmic background radiation whose temperature is 1.9 degree Kelvin (-271.2 degree Celsius). Other neutrinos are constantly being produced from nuclear power stations, particle accelerators, nuclear bombs, general atmospheric phenomenae, and during the births, collisions, and deaths of stars, particularly the explosions of supernovae.

https://icecube.wisc.edu/info/neutrino
Clusters includes galaxies and any material which is in the space between the galaxies. The force that holds the cluster together is gravity. The space between galaxies in clusters is filled with a hot gas. In fact, the gas is so hot (tens of millions of degrees!) that it shines in X-rays instead of visible light. In the image above, the hot X-ray gas (shown in pink) lying between the galaxies is superimposed on an an optical picture of the cluster of galaxies. By studying the distribution and temperature of the hot gas we can measure how much it is being squeezed by the force of gravity from all the material in the cluster. This allows scientists to determine how much total material (matter) there is in that part of space, thus a measure of Dark Matter.

Dark Matter Candidates

• Dark matter cannot be:
  • Ordinary dim stars because they would show up in infrared images
  • Cold gas because this gas would be detectable at radio wavelengths
  • Hot gas would be detectable in the optical, radio, and x-ray regions of the spectrum

• Objects that cannot be ruled out:
  • Tiny planetesimal-sized bodies, extremely low-mass cool stars, dead white dwarfs, neutron stars, and black holes
  • Subatomic particles like neutrinos
  • Theoretically predicted, but not yet observed, particles referred to as WIMPS (weakly interacting massive particles)
Dark matter cannot be seen directly with telescopes; it neither emits nor absorbs light or other electromagnetic radiation at any significant level. It is otherwise hypothesized to simply be matter that is not reactant to light.

The existence and properties of dark matter are inferred from its gravitational effects on visible matter, radiation, and the large-scale structure of the universe. According to the Planck mission team, and based on the standard model of cosmology, the total mass–energy of the known universe contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy.

Dark matter's existence is inferred from gravitational effects on visible matter and gravitational lensing of background radiation, and originally hypothesized to account for discrepancies between calculations of the mass of galaxies, clusters of galaxies and calculations based on the mass of the visible "luminous" matter these objects contain: stars, gas and dust of the interstellar and intergalactic medium.

The most widely accepted explanation for these phenomena is that dark matter exists and that it is most probably composed of weakly interacting massive particles (WIMPs) that interact only through gravity and the weak force.

https://globalscienceteam.wordpress.com/about/what-is-dark-matter
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
Cause of Activity in Galaxies

- Basic model
  - Black hole about the size of the 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 of gas maintained by nearby passing stars or material from collision with another galaxy
Cause of Activity In Galaxies

- 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
- Formation of Supermassive Blackholes
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 times more luminous than the Milky Way ($\sim 2 \times 10^{10} \, L_{\text{sun}}$)
Quasars

- 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).
Gravitational Lenses

- Light from a quasar may bend as it passes by a massive object in much the same way light is bent as it passes through a glass lens.
- The bending of light by gravity is a prediction of Einstein’s general theory of relativity.
- The bending light creates multiple quasar images and arcs that can be used to determine the mass of the massive object.
Gravitational Lenses

Intervening galaxy bends light.

One image of quasar looks like it is here.

Quasar

Another image of the quasar looks like it is here.
Galaxy Clusters

Galaxies are often found in groupings called **galaxy clusters**

- Galaxies within these clusters are held together by their mutual gravity
- Typical cluster is several million light-years across and contains a handful to several thousand galaxies
Rich Clusters

- Largest groups of galaxies - contain hundreds to thousands of member galaxies
- Large gravity puts galaxies into spherical distribution
- Contain mainly elliptical and S0 galaxies
- Spirals tend to be on fringes of cluster
- Giant ellipticals tend to be near center – cannibalism
- Contain large amounts ($10^{12}$ to $10^{14}$ $M_{\odot}$) of extremely hot X-ray emitting gas with very little heavy elements

Poor Clusters

- Only a dozen or so member galaxies
- Ragged, irregular look
- High proportion of spirals and irregulars

The Local Group
Galaxy Clusters

- In general, all clusters need dark matter to explain galactic motions and the confinement of hot intergalactic gas within cluster.

- Near clusters appear to have their members fairly smoothly spread out, while far away clusters (and hence younger clusters) are more ragged looking – this suggests that clusters form by galaxies attracting each other into groups as opposed to clustering forming out of a giant gas cloud.
Cosmology

- *Cosmology* is the study of the structure and evolution of the Universe as a whole
- How big is the Universe?
- What shape is it?
- How old is it?
- How did it form?
- What will happen in the future?
Cosmology

- What we seem to know now:
  - The Universe is expanding and is filled with a very low-energy background radiation
  - The radiation and expansion imply the Universe began some 13.7 billion years ago
  - The Universe began as a hot, dense, violent burst of matter and energy called the **Big Bang**
Observations of the Universe

- In the early years of the 20th century, astronomers envisioned the Universe as a static place with only the Milky Way and a few companions.
- It was not until the 1920s that astronomers realized the Universe was filled with other galaxies millions of light-years apart and that the Universe was expanding.
Observations of the Universe

- No matter which way you look (ignoring the zone of avoidance), you see about the same number of galaxies.
- The galaxies are not spread smoothly, but clump into groups.
- This “smooth clumping” implies a similar distribution for the whole Universe. There is no large scale structure.
- Cosmological Principle states that the Universe is homogenous and isotropic. No preferred center, looks the same in all directions.
Motion of Galaxies

- In general, a galaxy obeys the Hubble law: speed of recession is proportional to the galaxy’s distance, the proportionality given by the Hubble constant.
- The motion away is due to the expansion of space itself – not like bomb fragments going through the air, but like buttons attached to an expanding balloon.
Age of the Universe

- Running the Universe’s expansion backward implies all mass becomes confined into a very small volume, what was once called the “Primeval Atom”

- Assuming galaxies have always moved with the velocities they now have, the Hubble Law gives age for Universe of 14 billion years with $H = 70 \text{ km/s/Mpc}$

\[ D = Vt \]

Therefore, \( t = \frac{D}{V} \)

But according to the Hubble law, \( V = DH \)

Therefore, \( t = \frac{\frac{D}{H}}{H} = \frac{1}{H} \)
Are We at the Center of the Universe?

- The recession of distant galaxies often leads to the misconception that the Milky Way is the Universe’s center.
- However, because space is expanding, no matter where you are located, galaxies will move away from you – there is no preferred center.
- This lack of a preferred location is part of the cosmological principle.
The Cosmic Horizon

- The age of the Universe limits the distance we can see since the speed of light is finite
- In a static Universe, this distance is directly determined from its age and the speed of light
- The maximum distance one can see (in principal, but not necessarily in practice) is called the cosmic horizon
The Cosmic Horizon

- The space within the horizon is called the visible (or observable) Universe – there may very well be more to the Universe beyond.

For a 14 billion-year-old Universe, this radius is 14 billion light-years.
The Cosmic Microwave Background

- The proposed very-dense early Universe implied that it must have been very hot, perhaps 10 trillion K.
- It was proposed that as the Universe expanded and cooled, the radiation that existed at that early time would survive to the present as microwave radiation.
- This radiation was accidentally discovered by Arno Penzias and Robert Wilson in 1965 and has since then been referred to as the *cosmic microwave background* (CMB).
"Stretching" Radiation

As space expands it "stretches" the light waves moving through it, increasing their wavelength, $\lambda$.

Short wavelength implies *hot*. Long wavelength implies *cool*. 
The Cosmic Microwave Background

- The CMB follows a perfect blackbody spectrum with a temperature of 2.725 K (about 3 K, a bit above absolute zero)
- Measuring the anisotropy of CMB around 1-2 degrees or less
Power spectrum of CMB variations
Evolution of the Universe

- The Universe is currently expanding, but what of its future:
  - Will it expand forever
  - Will it stop expanding and collapse
Evolution of the Universe

• Expanding forever means that as all the stars consume their hydrogen, the Universe will become black and empty – this scenario is the open universe

• A Universe that collapses as a “Big Crunch” might lead to another “Primeval Atom”, leading perhaps to the birth of another universe – this scenario is the closed universe

• The expansion speed of the Universe becomes zero when the Universe has reached infinite size – this scenario is the flat universe
Evolution of the Universe

The energy content of the Universe depends on what type of universe we are in:

- An open universe has positive total energy
- A flat universe has zero total energy
- A closed universe has negative total energy
- In principal, if we measure the energy content of the Universe, we can tell what type it is
- The energy content of the Universe is the sum of its positive kinetic energy of expansion and its negative energy of gravitational binding (basically its mass content)
The Density of the Universe

- The mass density of the Universe gives an equivalent means of determining its total energy content and it’s easier to measure
The Density of the Universe

To determine if the Universe is open or closed, compare its density ($\rho$) to the **critical density**:

$$\rho_c = \frac{3H^2}{8\pi G}$$

Here $H$ is Hubble constant and $G$ is the gravitational constant.

The critical density for the Universe is approximately $10^{-26}$ kg/m$^3$ (or 10 hydrogen atoms per cubic metre).

- If $\rho > \rho_c$, the Universe is closed.
- If $\rho < \rho_c$, the Universe is open.

**WMAP** -- $9.47 \times 10^{-27}$ kg/m$^3$ density of Universe not enough.
• Another way to ascertain the Universe’s fate is to look at very distant galaxies – galaxies in the past – to see how fast the Universe’s expansion has slowed.

• Interestingly, using supernova in very far and faint galaxies as distance indicators, it appears the Universe is speeding up, not slowing down.
A Cosmological Repulsion?

How is this possible?

- Einstein’s general relativity equations include a *cosmological constant* that represents a repulsive force.
- When the expansion of the Universe was discovered, the cosmological constant was thought to be zero.
- Latest measurements imply this may not be the case.
- The additional expansion energy is called *dark energy*, and is a property of space itself.
- This dark energy contributes to the total mass of the Universe.
Einstein’s General Theory of Relativity is built around the **curved space**

Curved space is not easy to visualize, but there are two-dimensional models that can help
Positive Curvature

- **Positive curvature** (also called “closed”) resembles the surface of a sphere – parallel lines meet, and triangles have interior angles with a sum greater than 180°.
Negative Curvature

- Negative curvature (also called “open”) resembles the surface of a saddle – parallel lines never meet, and triangles have interior angles with a sum less than 180°.
Flat Curvature

- Flat curvature (what people typically think of as space) – parallel lines do not meet, and triangles have interior angles with a sum equal to 180°
Measuring the Curvature of Space

CMB provides another way

- CMB is extremely uniform across the sky except for tiny variations in brightness from place to place

https://map.gsfc.nasa.gov/media/121238/index.html
• The spatial sizes of these variations can be predicted based on conditions in the early Universe
• Analysis of variations indicate that Universe is flat with a non-zero cosmological constant