Cosmology In A Nutshell
Inflationary Hot Big Bang Model
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1. **Important Time Periods**
   - **1.1.** First few minutes after initiation of the Big Bang at T_0
     - **1.1.1.** Creation of Spacetime and Energy
     - **1.1.2.** Separation of Matter and Energy
     - **1.1.3.** Nucleosynthesis
   - **1.2.** Circa 300,000 years after T_0
     - **1.2.1.** Atom formation
   - **1.3.** Circa 50 million to 500 million years after T_0
     - **1.3.1.** Formation of first galaxies and stars
   - **1.4.** Circa 4.5 billion years after T_0
     - **1.4.1.** Formation of earth
   - **1.5.** Circa 13.5 billion years after T_0
     - **1.5.1.** Today
2. **Creation Of Spacetime and Energy**
   - **2.1.** What follows in section 2 is based on quantum field theory and therefore speculative. In the beginning, Quantum Fields existed. Spacetime and energy were embedded in the structure of the original quantum field and were not separate entities. Random fluctuations in the original quantum field exceeded an equilibrium threshold and triggered its transformation into a set of successor lower energy quantum fields, in which spacetime and energy were separate entities.
     - **2.1.1.** Spacetime is a single entity; not space and time, but spacetime. Spacetime is described by Einstein's theory of special relativity. Energy also emerges, infinitely hot, high frequency, short wavelength; more intense than the most intense radiation known today, gamma radiation.
     - **2.1.2.** Spacetime and energy emerge from a point; infinitely small. At initiation, the universe is spacetime and energy contained in a spacetime volume that is smaller than the size of the nucleus of one atom.
     - **2.1.3.** The Universe has evolved since the big bang (T_0) by continual expansion. Expansion is at different rates at various stages of evolution. Cosmological time and distance scales are hard to comprehend.
       - **2.1.3.1.** Time spans about 14 billion years, and important cosmological processes span extremely different time scales. Creation of matter and energy and nucleosynthesis span minutes. Formation of the first stars and galaxies does not begin until about a hundred million years later. Cosmic evolution of stars and galaxies thereafter occurs on scales of more than a billion years.
       - **2.1.3.2.** The universe begins as a point smaller than the nucleus of an atom and it spans a distance (spherical diameter) of 93 billion light years today. One light year is about 6 trillion miles.
     - **2.1.4.** The term Big Bang is a misnomer, there could be no explosive bang. Explosion requires pre-existing space into which energy is released.

2.2. Inflation.

2.2.1. Expansion of space and lapse of time have been proportional since T_0 (different power law mathematical relationships at various times), except during a very brief period of inflation, between about 10^{-35} and 10^{-33} seconds after T_0.

2.2.2. During inflation space expanded by > 10^{30} fold while time elapsed only by a factor of 10^2(from 10^{-35}to10^{-33}). In other words, space expanded exponentially as compared to time instead of proportionally.

2.2.2.1. During inflation the entire universe goes from a volume less than one nucleus to a volume ~ a sphere 6 feet in diameter.

2.2.2.2. The result of inflation is that at 10^{-33} seconds after T_0, the universe consists of a 6 foot diameter sphere containing an unimaginably large amount of energy confined in the bounds of existing spacetime, with nowhere to go except expand with spacetime. At one second after inflation the universe is a sphere about 1000 light years in diameter.

2.2.2.3. The energy is distributed evenly through spacetime, to better than 1 part in one billion. Cosmologists say that the universe was homogenous and isotropic, with very slight variations in energy density.

2.2.2.4. After inflation, the mathematical relationship between space and time is proportional, defined by a few power law relationships, each applicable during an era of evolution (eg. $x^{2/3}$ or $x^{4/3}$). At one year after inflation the universe is a sphere about 100,000 light years in diameter. (The rate of expansion slowed down by a factor of 100 as compared to the rate at 1 second after inflation.)

3. Separation of Matter from Energy.

3.1. Expansion of spacetime results in decreasing temperature, which in turn results in activation of a new set of quantum fields that produce matter from energy ($E=mc^2$).

3.2. Energy is in the form of photons, which have the dual characteristics of particles and waves. Electromagnetic energy spectrum, from highest to lowest energy: gamma radiation, x-ray, ultraviolet, visible light, infrared, microwave radio, and radio.

3.3. Matter takes the form of dark matter and regular matter.

3.3.1. The characteristics of dark matter particles are unknown. Dark matter does not interact with electromagnetic energy and is therefore not visible or detectable by any method using electromagnetic energy as a probe. Its presence is known because it generates gravity in the same way as regular matter, and the gravitational effects are observable. There is about 5 times more dark matter than regular matter in the universe.

3.3.2. Regular matter consists of several families or generations of quarks and leptons. Only the lowest energy family of quarks and leptons exist at energy levels in which particles persist for longer than milliseconds. The lowest energy quarks are the up quark and the down quark; these combine to form protons and neutrons. The lowest energy lepton is the electron.

3.3.3. When matter separates from energy and before nucleosynthesis, it exists as a gas of quarks and electrons. The quarks and electrons exist as matter and antimatter pairs, for example up quark and antiup quark and electron and positron. The ratio of matter to antimatter is nearly 1, but there is a slight surplus of matter over antimatter (the reason is uncertain).

3.3.4. The matter and antimatter pairs form and annihilate each other until the temperature drops below the threshold necessary to support these reactions of reciprocal transformation between matter and antimatter. When matter – antimatter creation and destruction becomes unsustainable, due to decreasing temperature, the annihilation reactions produce photons (energy) and the residual excess of matter particles (up and down quarks and electrons). The ratio of radiation photons to matter particles in the universe is 1.5 billion photons to each quark.

4. Nucleosysthesis.

4.1. What follows is based on particle physics, confirmed by observations in particle accelerators; so very little uncertainty.

4.2. A couple of minutes after T_0 the up and down quarks have combined to form protons and neutrons, but the temperature is high enough to support the inter-conversion of protons and neutrons, so they exist in roughly equal numbers in this state.

4.3. The proton is a stable particle (half life billions of years). The neutron is unstable with a half life of 15 minutes, but it becomes stable when it combines with a proton.

4.3.1. As the temperature drops near and below the threshold necessary to support proton neutron interconversion, the instability of the neutron begins to become apparent and when interconversion stops, the ratio of neutrons to protons is .2; 1 neutron for every 5 protons.

4.3.2. This initial ratio of neutrons to protons and the short half life of the neutron cause big bang nucleosynthesis to be very incomplete. Of the more than 100 elements, only Hydrogen, Helium, Lithium, and Beryllium nuclei are formed in big bang nucleosynthesis.

4.3.2.1. Hydrogen is ~74% of the nuclei, Helium is ~25%, and Lithium and Beryllium are ~1%. All other elements in the periodic table were made later in the evolution of the universe via nuclear fusion reactions in stars. Most of earth and its life forms are made of star dust.

4.4 Nucleosysthesis is finished before 5 minutes have elapsed after $T_{0.}$ What exists is a dense gas essentially consisting of Hydrogen and Helium nuclei as positive ions, free electrons, and high energy photons (several billion for each positively charged nucleus).

4.4.1 This state will persist for about 300,000 years, until the expansion of the universe has reduced the energy of the photons enough to permit formation of atoms of hydrogen and helium gas. After 300,000 years the universe is about 32 million light years in diameter.

5. Atom Formation.

5.1. The hydrogen and helium nuclei cannot capture electrons to form atoms of hydrogen and helium gas while the photons in the ionized plasma have energy sufficient to dislodge them. In this plasma state, the photons and free electrons continuously interact to form an integrated mixture.

5.1.1. When the temperature drops to about 3800 degrees Kelvin, the photons cease to have enough energy to prevent capture of the electrons by the hydrogen and helium nuclei. As the electrons are bound to nuclei to form atomic hydrogen and helium gas, the photons are released to freely travel through spacetime until they happen to collide with a particle (or a particle detector).

5.2. When the photons were released, 300,000 years after T_0, they were in the form of high frequency infrared radiation.

5.2.1. These photons are observable today, 13 billion years later, as the cosmic microwave background radiation (CMB). Spacetime has expanded during the 13 billion years since the release of the CMB photons by a factor of about 1100, and the wavelength of the CMB photons has also been stretched by a factor of 1100. The CMB photons that were released as infrared photons are now microwave radio waves, observed with radio telescopes.

5.2.2. The discovery of the CMB photons in about 1965 provided the most compelling evidence for the big bang.

5.2.2.1. The CMB is uniform to a level of parts per million and the same everywhere you look in the universe. The big bang model predicted the release of the CMB photons, but it was unexpected to find them in the form of microwave radio radiation.

5.3. The atomic hydrogen and helium gas continues to expand and cool along with spacetime. After millions of years the gas is very cold, but too tenuous to form molecular gas (eg H_2).

5.4. The development of the universe in the era that begins between 50 and 500 million years after T_0 is driven by gravity and dark energy. These two forces create the structure of the universe that is observed today.

5.4.1. The force of gravity has been known and studied for hundreds of years; modern standard physics is based on Newton's equations of gravity, motion, and acceleration. Einstein's theory of general relativity is the current theory of gravity, and it reduces to the Newtonian form under conditions of speed much less than the speed of light and weak gravitational fields, like that created by Earth's mass.

5.4.2. Dark energy was a hypothetical force invented by Einstein (it was named the cosmological constant) to get the equations of general relativity to match a static universe, which was the accepted model at the time. It was a force that opposed gravity on very large length scales by driving expansion; gravity causes contraction and dark energy causes expansion. The universe evolves according to the ratio / balance between these two large scale cosmological forces. (Einstein thought they should be equal to create a static universe; spacetime expansion was discovered later.)

5.4.2.1. Dark energy currently is thought to be an energy density quantum field that has been present since the big bang and is fundamental to the overall structure of the quantum fields that underly all of the energy, matter, spacetime, and everything else that has a physical existence. Dark energy was the force responsible for inflation and it is the force that is driving the expansion of spacetime in the present cosmological era. Everything about the specific nature of dark energy is speculative.

6. Formation of Galaxies.

6.1. Qualitatively gravity works by amplifying any slight difference in density of mass. Slightly over dense areas of mass become denser and slightly under-dense areas of mass become less dense. It's called the Matthew effect, to he that has much, more will be given, and to he that has little, more will be taken away.

6.2. By itself, gravity causes over-dense areas to increase in density exponentially. This would lead to compression of matter and a collapse of spacetime that is typically seen in black holes.

Gravity is constrained on small scales by pressure, which is why black holes are rare. Pressure waves or fluctuations caused by compression of particles of dark matter or regular matter (hydrogen and helium atoms) builds up at a rate that is dependent on the speed of sound in the gas of hydrogen and helium within some volume.

6.2.1. There is a characteristic length and volume scale (determined by equations based on sound speed), and a characteristic mass contained within that volume, that defines the volume within which gravitational collapse of gas to form stars will occur. The characteristic length and mass are called the Jeans length and the Jeans mass. In this volume size, pressure and gravity are close enough in strength to cause oscillations between phases in which gravity dominates and causes contraction and then pressure reacts to slow contraction such that the radius of the volume concentrically decreases slowly.

6.2.2. The approximate size of this volume within which gravity and pressure will cause the formation of groups of stars (ie a protogalaxy) is between 1000 and 10,000 times the volume of our solar system (10^{15} meters in diameter). Note this is smaller than most galaxies, but adjacent protogalaxies can merge to form a single larger galaxy.

6.3. Gravitational instability affects dark matter first, because: a) there is 5 times more dark matter than regular matter, and b) dark matter does not interact with radiation, so it does not become hot and ionized and there is no electric charge opposing compression.

6.3.1. Dark matter forms shells, known as dark matter halos, within which galaxies of stars made from regular matter will form. All galaxies are embedded inside of a dark matter shell that surrounds the luminous stars made of hydrogen and helium in the galaxy.

6.3.1.1. The dark matter halo is invisible, but its gravitational field is obvious. The rotational seed of stars in a galaxy can be measured, and they orbit much too fast to be held in their orbits by the gravity of the matter in the stars themselves. The additional matter necessary to generate the gravitational field necessary to explain the orbital velocities is the dark matter halo.

6.3.1.2. Dark matter halos and their protogalaxies can merge and grow in size by a process known as hierarchical clustering.

6.4. Hydrogen and helium gas aggregate within the gravitational wells created by dark matter halos. Galaxies form by the gravitational collapse of clouds of hydrogen and helium gas within dark matter halos. Gravitational compression of hydrogen and helium gas is more complex than the gravitational compression of dark matter because regular matter interacts with radiation and heat.

6.4.1. Hydrogen and helium gas must be compressed until its density is at least 3 times the density of the dark matter halo before it can collapse to form stars. The excess density is required to overcome the tidal gravity of the dark halo. When the density increases sufficiently, the hydrogen gas becomes molecular (H_2 as compared to H_1 atomic hydrogen). Stars from in clouds of molecular hydrogen.

6.4.2. Galaxy sizes range between 10^7 and 10^{12} solar masses. This range results because 10^7 is the minimum mass (within a Jeans volume) which can generate a gravitational field that is strong enough to cause collapse, and 10^{12} is the mass of gas that will produce the maximum temperature, via molecular collisions, that can be cooled enough by various processes to permit compression of the gas to the density that is necessary to form stars.

6.4.3. The first stars form in galaxies in a random process and they are distributed in an elliptical distribution. After the first stars are formed, the density of gas in the new galaxy is decreased, and star formation slows down, which gives the gas time to settle into a flattened disk. Thereafter stars form in the disk of gas, typically in spiral arm structures.

6.4.3.1. Galaxies are classified as elliptical or spiral galaxies (the arms are in a planar disk), but most galaxies have elliptical and spiral features. They are classified according to the dominant feature.

6.5. Galaxies are the building blocks of the universe.

6.5.1. Galaxies merge. The gravitational fields of galaxies in close enough proximity to each other bring them together and the larger galaxy absorbs the smaller one, a process called cannibalization. Galaxies are mostly empty space and clouds of tenuous gas, so mergers rarely result in collisions of individual stars. However, some mergers can disrupt orbital patterns due to violent tidal fluctuations in the gravitational fields.

6.5.2. At the center of most galaxies, the gravitational field eventually becomes so intense that it forms a black hole. Spacetime lines of curvature (known as geodesics) spiral down to an infinitely small point, or singularity, in a black hole. Black holes are invisible because photons must follow the curvature of spacetime and so no radiation, for example light, can be emitted from inside of a black hole because no geodesic - line of spacetime curvature extends beyond the horizon.

6.5.2.1. Although the black hole itself is invisible, its gravitational field is so intense that it creates circular orbits outside the horizon that spiral into the black hole. Matter that is drawn into this area forms an accretion disk which is pulled into the black hole. The conditions in the accretion disk include ionized gas at extremely high velocities, powerful magnetic fields, and extreme temperatures that destroy matter and covert it into energy. These accretion disks produce jets of hot plasma that are ejected out several light years from the black hole. Black holes and their accretion disks are known as Active Galactic Nuclei and the most intense of these are Quasars, which can emit as much energy as a billion suns.

6.5.3. The Milky Way probably formed about 13 billion years ago, about 500,000 million years after T_0. Our sun and its solar system formed about 4.5 billion years ago, so it is in the newer part of the galaxy; about 3/4^{ths} of the way out in a spiral arm within the galactic disk.

7. Formation of Stars.

7.1. Stars form via gravitational collapse of clouds of molecular hydrogen and helium, called Giant Molecular Clouds (GMC). A typical GMC contains 10^7 solar masses of gas within a volume with a diameter of several hundred light years. The GMC has a fractal structure comprised of ~10 nested molecular clouds and the GMC is surrounded by a more tenuous cloud of atomic hydrogen. The density of gas varies within the GMC, between 10 and 10^4 gas molecules per cubic centimeter.

7.1.1. Each nested GMC will fragment as it collapses and produce on the order of hundreds of stars. Fragmentation occurs because the Jeans mass (proportional to 1/density) decreases as the density increases and consequently the gravitational field splits into volumes with independent central points. The most over-dense regions become new smaller clouds with their own gravitational fields that cause them to contract toward their own centers.

7.2. The initial phase of collapse of the molecular gas is directed radially, and it creates an "embryo" protostar that contains less than .1 solar mass of hydrogen compressed in a small sphere. The protostar subsequently grows by accretion of surrounding gas; accretion generates about 99% of a star's total final mass. The accretion occurs through both radial in-fall and rotational spiraling. The proportion of accretion by radial in-fall and rotational in-fall vary among stars, but rotational in-fall becomes more dominant as the star gets bigger.

7.3. Evolutionary stages of accretion have been defined as: Stage 0, Stage I, Stage II, and Stage III.

- **7.3.1.** Stage 0 consists of cycles of increase in mass caused by gravitational in-fall of gas, increased compression of the gravitational field, and a rebound pressure stabilization at a new larger spherical radius. Temperature is too low to trigger nuclear fusion. Stage 0 lasts about 10,000 years.
- **7.3.2.** Stage I consists of increased rotational in-fall of gas, which produces energy by high speed collisions of gas molecules like those produced in particle accelerators. Small jets of high energy photons are ejected out into space. The star keeps growing in mass and size by cycles of collapse and pressure rebound stabilization at larger radii. The star achieves more than 95% of its eventual size in Stage 1. Temperature is too low to trigger nuclear fusion, but the radiation emitted by the accretion process makes the protostar visible. Stage I lasts about 100,000 years.
- **7.3.3.** Stage II consists of violent dispersion of the remainder of the accretion disk via high speed collisions of the gas molecules, intense magnetic fields, and turbulent flows of gas. Large jets of high energy photons are ejected out into space; analogous to a black hole but on a much smaller scale. Stage II is called the T Tauri stage and it lasts between several hundred thousand to one million years. The lowest energy nuclear fusion (deuterium to helium) begins in stage II. T Tauri stars emit radiation mainly in the high infrared range of the electromagnetic spectrum.
  - **7.3.3.1.** Planets are formed from the remnants of the accretion disks of stars. Only some stars form planets from their accretion disks. If the accretion process is too violent / turbulent the accretion disk is dissipated by in-fall and ejection back into space. (The book Story of Earth does a good job of describing the process of planet formation.)
- **7.3.4.** Stage III consists of the beginning of standard nuclear fusion reactions. In this stage the star reaches what is known as hydrostatic equilibrium. The star no longer significantly changes its radius, because the energy released by fusion balances the gravitational field. Stage III marks the transition of the star into a new classification system, known as the main sequence.

7.4. Stars range in size between about .1 solar mass to about 150 solar masses. Larger stars have higher temperatures and shorter lifetimes. The Main Sequence classification system consists of 7 classes, from biggest to smallest: 1) O Stars, temp ~30,000 degrees Kelvin, 2) B Stars, temp ~20,000 degrees, 3) A Stars, temp ~10,000 degrees, 4) F Stars, ~7,000 degrees, 5) G Stars, ~6,000 degrees, 6) K Stars, ~4000 degrees, and 7) M Stars, ~3000 degrees.

- **7.4.1.** The Sun is a G class star.
- **7.4.2.** The lifetime of O Stars is on the order of 10 million years. The lifetime of G Stars like the sun are on the order of 10 billion years.

7.5 Stars create all of the elements in the periodic table that are heavier than hydrogen and helium via nuclear fusion reactions. All stars on the main sequence can fuse hydrogen to form helium. Medium mass stars have sufficient mass, gravitational compression, and high temperature to fuse helium to form the elements up to carbon and oxygen. Only the massive stars have enough mass, gravitational energy, and high enough temperature to generate the fusion reactions that generate the elements from carbon / oxygen through iron. Iron is the most stable nuclear configuration and the heavier elements can't be created by regular fusion reactions.

7.5.1 End of life stellar processes are the means by which: a) the elements created by stellar fusion are dispersed in the universe, and b) the elements heavier than iron are made.

7.5.2 End of life stellar processes result when the star runs out of fuel that it can fuse to create energy that offsets gravity and maintains the star in hydrostatic equilibrium. There are two basic end of life processes, each with variations, one for low and medium mass stars and one for high mass stars.

7.6 Low and medium mass stars contract down to a fraction of their stable size as they run out of fuel and their cores consist of carbon nuclei and electrons. The intense gravitational field forces the electrons out of their normal atomic orbitals and they form a layer of electrons that surround the carbon nuclei. The displaced electrons generate a type of quantum pressure that can offset the gravitational field and the stabilized core forms a white dwarf star. In the process of forming the carbon and electron core, all of the outer layers of the star are first greatly expanded and transformed to form a red giant. The outer layers of the red giant are expelled into space either gradually or violently, and thereafter only the white dwarf core is left. The expelled layers seed the universe with the elements up through carbon and oxygen.

7.7 High mass stars also contract down to a fraction of the stable size as they run out of fuel, but they have the energy to fuse many more of the heavier elements, and the star forms concentric layers, with deeper layers fusing heavier elements, down to the core of iron. The core consists of iron nuclei and a layer of electrons, but the gravitational field overcomes the quantum pressure of the electrons and forces them to fuse with the protons in the iron nuclei so that the core becomes a sphere of neutrons. The neutron creation process destroys nuclei and releases the nuclear binding energy, which causes all of the outer layers of the star and some of the core to explode. This explosion is one of the two main types of supernova. The explosion outflow contains protons from the outer layers, excess neutrons from the outer part of the core, as well as electrons, neutrinos, and radiation. This nuclear mixture permits the elements heavier than iron to form among the abundant protons, neutrons, and electrons.

7.7.1 If the residual core of neutrons is less than about 3 solar masses it forms a neutron star. If it is greater than 3 solar masses its gravity will collapse it down to a singularity and form a black hole.