ASTR-1020: Astronomy II
Course Lecture Notes
Section XI

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Edition 4.0

Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1020: Astronomy II at East Tennessee State University.

XI. Cosmology — The Study of the Origin, Structure, and Evolution of the Universe

A. Olber's Paradox — Why does it get dark at night?

1. If the Universe is static, infinite, and eternal, we should light in every direction we look. [Why do you think this should be the case?]

2. The Universe is expanding (hence not static) and is not eternal! $\Longrightarrow$ Big Bang Theory — it had a beginning!

a) Light gets redshifted out of the visible band.

b) As we look out, we look back in time. We cannot look infinitely far out since, sooner or later, we will see the Big Bang.

i) How long ago did this happen? We can estimate this time by calculating when all the galaxies were at the same position. This can be done through the use of Hubble's Law.

ii) In physics, velocity is defined as the ratio of a distance traveled, d, during a given amount of time, t: $v = d/t$.

iii) Rewriting this gives $d = vT$, where here d = galaxy distance, v = galaxy velocity, and T = time of flight from origin. But from Hubble's Law, $v = H_\circ d$, so

$$\begin{aligned} T &= \frac{d}{v} = \frac{d}{H_\circ d} = \frac{1}{H_\circ} = \frac{1}{71 \text{ km/sec/Mpc}} \\ &= 14 \text{ billion years,} \end{aligned} \qquad \text{(XI-1)}$$

where the answer is derived from converting Mpc into km and converting seconds to years. We can factor these conversions into the above relation and write the the equation for the approximate age of the Universe as

$$\boxed{T = \frac{1}{H_\circ(\mathrm{km/s/Mpc})} \times 10^{12} \text{ years}} \qquad \text{(XI-2)}$$

iv) Note that if $d > 14$ billion light years for a galaxy, we would not have seen it yet since light would not have had enough time to reach us ⟹ 14 billion light years is the approximate size of the **observable universe**.

B. The Big Bang Theory

1. The Universe started in an extremely small, hot, and dense state. As we go backwards in time, the Universe gets progressively smaller, hotter, and denser.

a) The Big Bang occurred everywhere in space, not just at one location ⟹ we are in the Big Bang!

b) Galaxies were <u>not</u> thrown apart ⟹ the fabric of space itself is expanding and the galaxies move apart as a result.

2. Note that the Big Bang Theory is based upon two postulates (*i.e.*, assumptions) called the **Cosmological Principle**:

a) **Homogeneity** — matter is uniformly distributed in space on a very large scale ($d > 100$ Mpc).

b) **Isotropy** — the Universe looks the same in every direction.

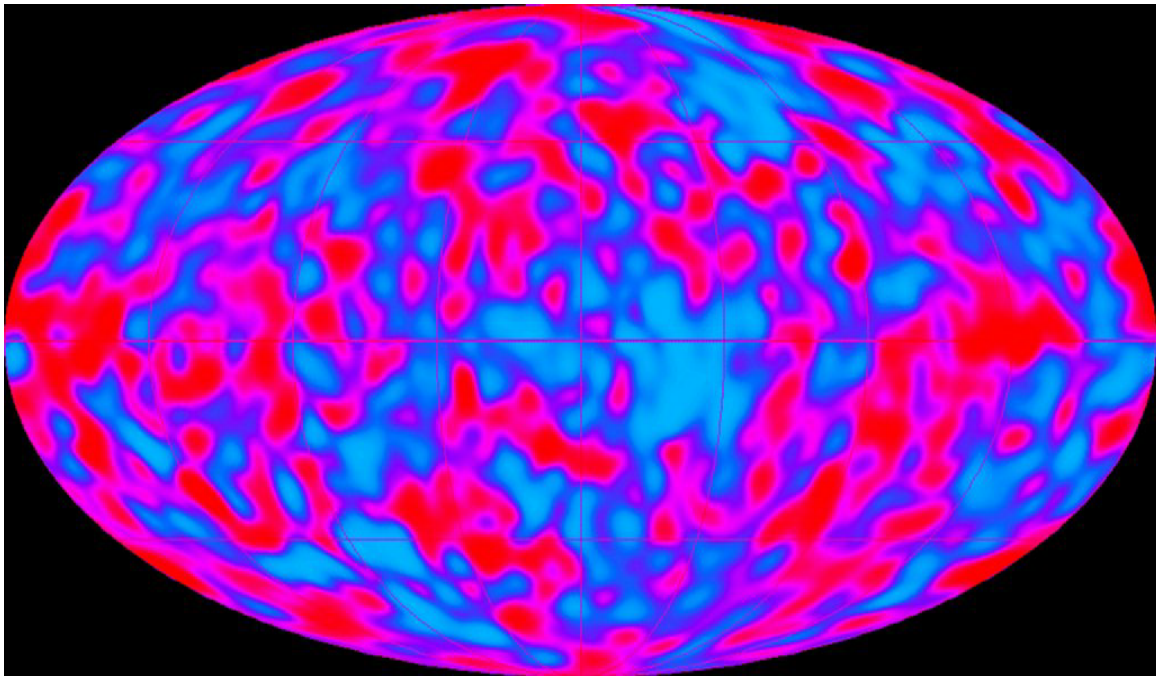

Figure XI–1: Cosmic Microwave Background as observed by COBE. This microwave image of the sky shows the variations in the Universe's temperature at recombination time. Blue represents regions of cooler gas, and red represents regions of hotter gas.

3. In addition to these, two additional assumptions are typically included when describing the Big Bang:

a) **Universality** — physical laws are the same everywhere in the Universe at all times.

b) **Cosmological Redshifts** — redshifts are caused by the expansion of the Universe through the Doppler Effect.

4. We see the Big Bang fireball in every direction as microwave blackbody radiation $\Longrightarrow$

3 K Cosmic Microwave Background (CMB) radiation.

a) When this light was emitted, the Universe was very hot.

b) As the Universe expanded, this light was redshifted until today it is microwave light $\Longrightarrow$ the redshift of this light is $z = 1100$, whereas the farthest quasar is at $z = 6.43$.

c) Penzias and Wilson discovered this CMB in the early 1960's, confirming theoretical predictions of the Big Bang Theory made by Dicke and Peebles. Penzias and Wilson later won a Nobel Prize for their discovery.

  i) Penzias and Wilson made these observations from the ground and their instrument was not sensitive enough to see any variation in this background glow.

  ii) This presented a problem since the current Universe has structure, how did this structure then arise?

d) The COsmic Background Explorer (COBE) spacecraft was launch in the early 1990's to investigate this background radiation (see Figure XI-1).

  i) It found the Universe radiates as a perfect blackbody (after the Solar System's motion and Milky Way's glow are subtracted) at a temp of 2.726 K.

  ii) COBE did detect small variations in the thermal distribution in the CMB on the order of 1 part in 100,000.

  iii) This variation is refereed to as the **intrinsic anisotropy**.

  iv) This intrinsic anisotropy shows that by the time this radiation was emitted (approximately 300,000 years after the Big Bang), inhomogeneities in the mass-energy of the Universe had begun which would later form the galaxies.

e) More recently, the Wilkinson Microwave Anisotropy Probe (WMAP) has observed this background at even higher spatial resolution (see Figure XI-2).

i) WMAP has determined the most accurate value of Hubble's constant (71 km/sec/Mpc) based on the pattern of the temperature variations.

ii) This temperature variation also gives the age of the Universe (*i.e.*, the time since the Big Bang) as 13.7 billion (1.37×10^{10}) years.

iii) Finally WMAP has shown that we live in a flat (in a 3-dimensional sense) space-time (discussed in detail shortly).

5. As the Universe expands, it should slow down due to the gravitational pull of one galaxy on another.

a) Are there enough galaxies (*i.e.*, mass) to stop the expansion?

i) If the Universe's mass density, ρ, is less than a critical density, $\rho < \rho_c$, gravity will not halt the expansion $\Longrightarrow$ an **Open Universe**.

ii) If $\rho > \rho_c$, gravity will halt the expansion and cause a contraction down to a *Big Crunch*! $\Longrightarrow$ a **Closed Universe**.

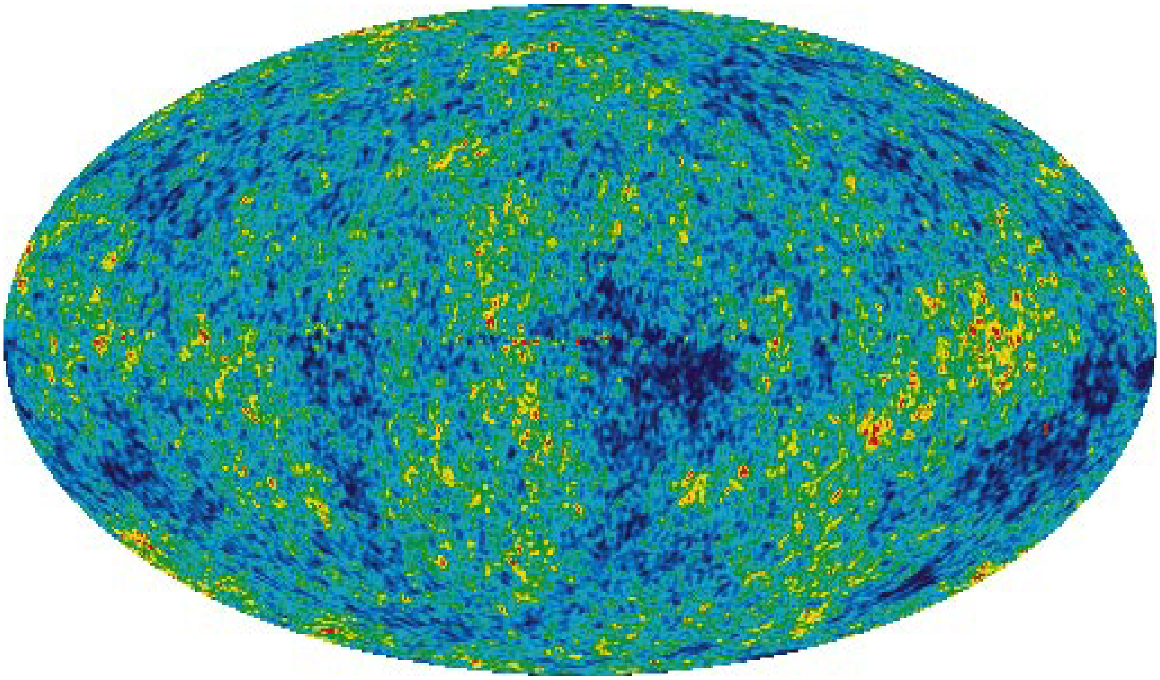

Figure XI–2: Cosmic Microwave Background as observed by WMAP. Note the higher spatial resolution as compared to the COBE map. The range of temperature on this map is ±200 microKelvin (2×10^{-6} K) of the 2.726 K average temperature.

iii) The Universe may be able to rebound (Big Bang) and start over again $\Longrightarrow$ an **Oscillating Universe**.

iv) If $\rho = \rho_c$, gravity will halt the expansion after an infinite amount of time $\Longrightarrow$ a **Flat Universe**.

v) Using general relativity, the critical density can be determined with knowledge of the Hubble constant. Using $H_\circ = 71$ km/sec/Mpc gives $\rho_c = 8.8 \times 10^{-27}$ kg/m^3.

b) The deceleration of the Universe is measured with the quantity $q_\circ$ — the **deceleration parameter**.

i) For an open universe, $q_\circ < 1/2$.

ii) For a closed universe, $q_\circ > 1/2$.

iii) For a flat universe, $q_\circ = 1/2$.

iv) If there were no mass in the Universe, $q_\circ = 0$.

c) Another parameter that is often used is the density parameter: $\Omega_\circ = \rho_\circ/\rho_c$. By knowing the value of $\Omega_\circ$, we will know the overall shape (*i.e.*, **curvature**) of the Universe in 4 dimensions and know the final fate of the Universe (see Figures XI-3 and XI-4):

Structure of the Universe

Type	Geometry	Curvature	Density Parameter	Deceleration Parameter	Age
Closed	Spherical	Positive	$\Omega_\circ > 1$	$q_\circ > \frac{1}{2}$	$T_\circ < \frac{2}{3}(1/H_\circ)$
Flat	Flat	Zero	$\Omega_\circ = 1$	$q_\circ = \frac{1}{2}$	$T_\circ = \frac{2}{3}(1/H_\circ)$
Open	Hyperbolic	Negative	$0 < \Omega_\circ < 1$	$0 < q_\circ < \frac{1}{2}$	$\frac{2}{3}(1/H_\circ) < T_\circ < 1/H_\circ$
No Matter	Hyperbolic	Negative	$\Omega_\circ = 0$	$q_\circ = 0$	$T_\circ = 1/H_\circ$

d) What is ρ of the Universe?

i) Galaxy counting: $\rho_{\rm gal} = 3 \times\ 10^{-28}$ kg/m^3

(25 times too small → open)

ii) Deuterium (^{2}H) abundance (baryons): $\rho_b = \rho_{\rm matter} = 7 \times 10^{-28}$ kg/m^3

($\rho_{\rm matter}$ is 11 times too small → open)

iii) Light: $\rho_{\rm rad} = a\,T_{\rm rad}^4/c^2$ and $T_{\rm rad} = 2.73$ K,

$$\begin{aligned}\rho_{\rm rad} &= 6.5 \times 10^{-31}\ {\rm kg/m^3} \\ \rho_{\rm rad} &\ll \rho_{\rm matter}\end{aligned}$$

— Today *matter* dominates the Universe!

— Radiation dominated at earlier times.

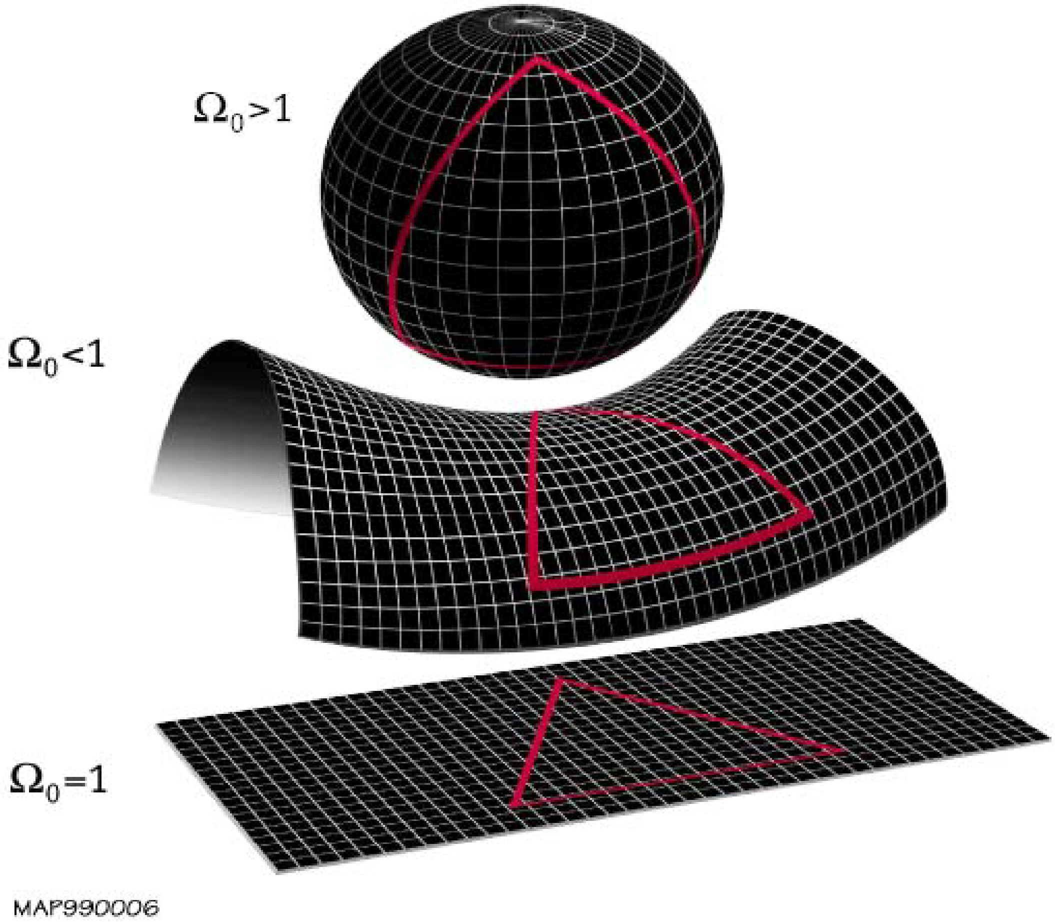

Figure XI–3: Three possible shapes of the Universe as a function of $\Omega_\circ$. Note that in these pictures, we represent our 3-dimensional space as a 2-dimensional surface. The *top* picture shows a *positive* curvature (*i.e.*, spherical shape) with $\Omega_\circ > 1$ ($\rho > \rho_c$). The *middle* picture shows a universe with $\Omega_\circ < 1$ ($\rho < \rho_c$). This universe has a *negative* curvature — a hyperbolic (*i.e.*, saddle) shape. The *bottom* picture shows a universe with $\Omega_\circ = 1$ ($\rho = \rho_c$) which is flat (*zero* curvature) space.

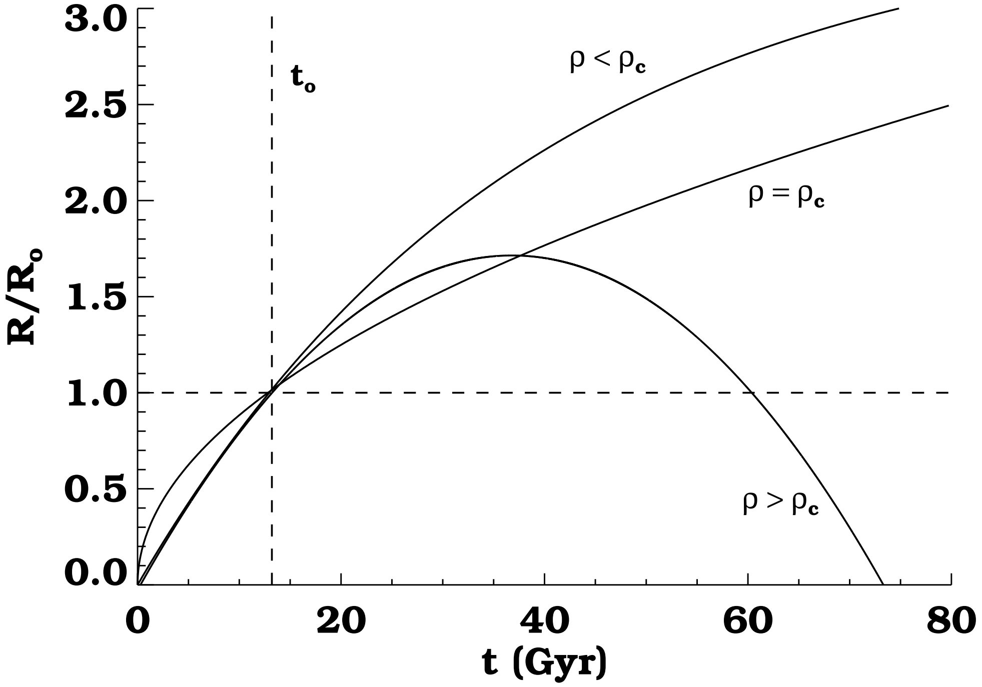

Figure XI–4: Histories of three different curvature universes as a function of the density parameter. Note that the present size of the Universe (hence, present time) is indicated by $R = 1$.

6. If the Universe had gone through an *Inflationary stage* (see §XI.D.4), then the Universe is essentially flat and $q_\circ = 1/2$.

a) One of the key projects of the *Hubble Space Telescope* is to accurately measure Hubble's constant ($H_\circ$). This project has determined that $H_\circ = 72$ km/s/Mpc with an uncertainty of 10% (note that WMAP measures it more accurately at 71 km/s/Mpc with an uncertainty of 4%).

b) Using these values of $q_\circ$ and $H_\circ$, we can ascertain the current mass-energy density of the Universe:

$$\begin{aligned}\rho_\circ &= \frac{3H_\circ^2 q_\circ}{8\pi G} = \frac{3 \cdot \left(\frac{71 \text{ km/s} \times 10^3 \text{ m/km}}{10^6 \text{ pc} \times 3.0856\times10^{16} \text{ m/pc}}\right)^2 \cdot (1/2)}{8\pi\,(6.668 \times 10^{-11} \text{ N m}^2/\text{kg}^2)} \\ &= 4.7 \times 10^{-27} \text{ kg/m}^3 \ ,\end{aligned}$$

or 6.6 times bigger than the baryonic matter we can measure (and see).

c) As such, astronomers have introduced a term called **dark matter** — matter which is <u>not</u> made up of protons and neutrons and cannot easily be seen.

d) So, 87% of the Universe seems to be composed of this dark matter! The race is on throughout the astrophysical community to try and find the identity of this hidden mass.

e) Remember, galactic rotation curves also show that there is a large amount of matter in the vicinity of galaxies that cannot be seen. It is thought that this dark matter deduced from cosmology is the same dark matter deduced from the rotation curve of our and other galaxies.

7. Recently, distance-redshift measurements of supernovae explosions in distant galaxies indicate, however, that the Universe may be accelerating instead of decelerating!

a) The field equations from general relativity produce a constant term called the **cosmological constant** (Λ).

i) Einstein's field equations for the Universe produce an *equation of motion* (like Newton's 2nd law) of

$$a(t) = (-4\pi G\rho(t) - \Lambda)\,\frac{R(t)}{3}\ , \qquad \text{(XI-3)}$$

where a is the acceleration of the Universe's expansion, ρ is the mass-energy density, R is the *size* of the Universe, and t is the time since the Big Bang.

ii) As can be seen, a, ρ, and R are all functions of time — they can change over time.

- **iii)** If the Universe is *slowing up*, then its acceleration is less than zero ($a < 0$) — a deceleration.

- **iv)** If the Universe is *speeding up*, then its acceleration is greater than zero ($a > 0$).

- **v)** If we lived in a static Universe (one that doesn't change with time), the cosmological constant would have to equal $-4\pi G\rho$, since 'a' would have to be zero in such a case, due to the fact that Δv and ΔR would both have to be zero over time. From this, the mass-energy density would remain constant for all time (since Λ is constant and the Universe's size would not be changing).

- **vi)** From this realization, the cosmological constant works in the opposite sense as gravity (*i.e.*, $G\rho$) due to the negative sign $\Longrightarrow$ **it acts like an anti-gravity** (assuming Λ has a positive value).

- **vii)** The term $\Lambda\, R/3$ is sometimes called the **cosmic repulsion term** of the Universe's equation of motion.

b) Einstein originally had a non-zero value for this to keep the Universe from changing size $\Longrightarrow$ astronomers and physicists of the late 19th and early 20th centuries thought that the Universe was *static*.

c) When Einstein learned from Hubble that the Universe was expanding, he went back and set $\Lambda = 0$ to let his model for the Universe expand.

d) A non-zero value for Λ allows for the possibility that empty space-time ($\rho = 0$, a universe with no matter in it) might be curved.

e) Note that the actual value for Λ is set from the initial conditions of the Universe at time zero. Since we can't see past the CMB, we cannot see the Big Bang itself. Hence, we have to try and determine this cosmological constant from observations coupled with the field equations of general relativity.

f) Although it would require a little calculus (which we won't show here), under a few assumptions of the geometry of the Universe, an expression for the cosmological constant can expressed in terms of current values of Hubble's constant ($H_\circ$), the deceleration parameter ($q_\circ$), and mass-energy density of the Universe ($\rho_\circ$):

$$\Lambda = 4\pi G\rho_\circ - 3q_\circ H_\circ^2 \quad . \tag{XI-4}$$

g) In 1922, Alexander Friedmann derived a set of equations (called the **Friedmann equations**) that describe the expansion of space in homogeneous and isotropic models of the universe within the context of general relativity including the use of the cosmological constant.

  i) He was able to show that for $\Lambda > 0$, an accelerated expanding universe can result as shown in Figure XI-5.

  ii) Such a universe matches what the recent supernovae observations have demonstrated about the history of the Universe — an initial deceleration followed by a continuous acceleration.

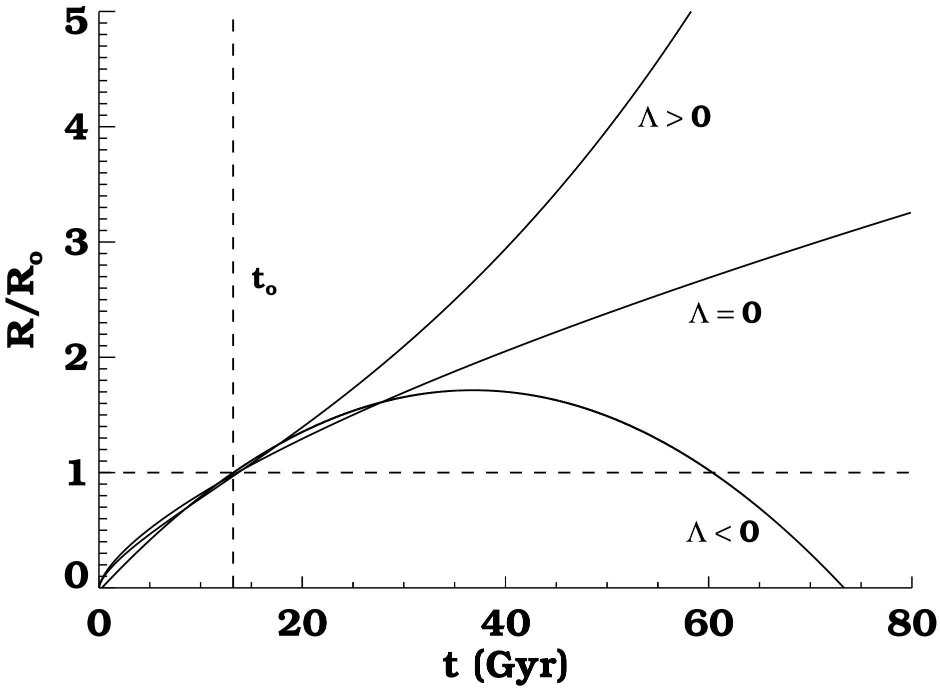

Figure XI–5: Histories of flat modified Friedmann model universes for various values of the cosmological constant Λ. Note that the present size of the Universe (hence, present time) is indicated by $R = 1$.

Example XI–1. What must the cosmological constant be for the best estimates of the parameters listed in Eq. (XI-4)?

$$\begin{aligned}\Lambda &= 4\pi(6.668 \times 10^{-11}\ \mathrm{N\ m^2/kg^2})\,(4.7 \times 10^{-27}\ \mathrm{kg/m^3}) - \\ &\qquad 3\left(\frac{1}{2}\right)\left(\frac{71\ \mathrm{km/s}\ \times 10^3\ \mathrm{m/km}}{10^6\ \mathrm{pc}\ \times 3.0856 \times 10^{16}\ \mathrm{m/pc}}\right)^2 \\ &= -3.9 \times 10^{-36}\ \mathrm{s^{-2}}\quad .\end{aligned}$$

From this, we can calculate what the acceleration of the Universe is due to this cosmological constant term (use the best estimate of the radius of the Universe to be 14 billion light years = 1.3×10^{26} m):

$$\begin{aligned}a_\Lambda &= \frac{\Lambda\, R}{3} = \frac{(-3.9 \times 10^{-36}\ \mathrm{s^{-2}}) \cdot (1.3 \times 10^{26}\ \mathrm{m})}{3} \\ &= -1.7 \times 10^{-10}\ \mathrm{m/s^2}\quad .\end{aligned}$$

Now, since the acceleration due to gravity on the Earth's surface is 9.80 m/s^2, that's 58 billion times larger than the acceleration due to the cosmological constant — unmeasurable on the Earth's surface (or by any large gravitating body). It only shows its presence on the very large scale!

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8. This "antigravity" force caused by $\Lambda > 0$ and resulting in our Universe's expansion to currently accelerate, has been affectionately called **dark energy** by many astronomers.

- **a)** It was given this name due to the fact that there is evidence for "dark matter" in the Universe as previously described.

- **b)** Based on the WMAP observations and the standard model of cosmology, dark energy currently accounts for 74% of the total mass-energy of the Universe (see Figure XI-6).

C. Particles and Forces

1. Before discussing the history of the Universe, we need to understand the 4 natural forces in nature and their effects on particles in the Universe.

2. There are 4 natural forces (*i.e.*, those forces associated with force fields). In order of strength they are:

- **a)** **Strong interactions**: Force that binds nucleons together — acts over a range of $\sim 10^{-13}$ cm. **Hadrons** participate in the strong force. The smallest component particle of a hadron is called a **quark**. This force is mediated by field particles called **gluons**.

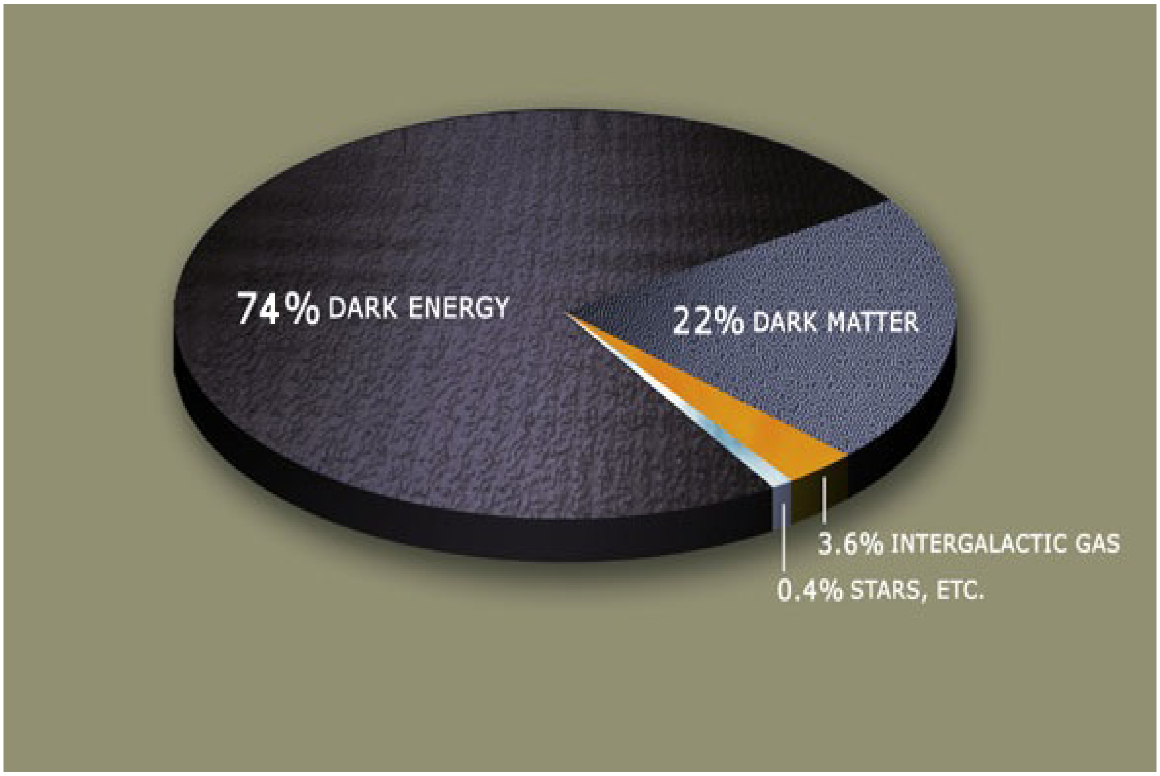

Figure XI–6: Estimated distribution of dark matter and dark energy in the Universe.

b) **E/M interactions**: Force between charged particles which has an infinite range that falls off as $1/r^2$. This force is 100 times weaker than the strong force, however it is what holds atoms and molecules together. This force is mediated by the **photon** field particle.

c) **Weak interactions**: These are responsible for β-decay of nuclei (*i.e.*, radioactivity) — 10^{-13} times as strong as strong interactions with a range $\ll 10^{-13}$ cm. The **intermediate vector boson** (often called **weakons**) mediates this force.

d) **Gravitational interactions**: These are by far the weakest of the interactions on the microscopic scale, typically about 10^{-40} times as strong as the strong interactions on nuclear scales. Gravity is another infinite, $1/r^2$ force, except it is charge independent — as such, this force dominates all others on a cosmic scale. The (yet to be discovered) **graviton** has been proposed as the particle that mediates the gravitational force.

3. There are 2 main groups of particles that make up all matter and energy:

a) **Elementary particles**: These are particles that make up matter. They are subdivided into 3 groups:

i) **Leptons** (*light* particles) include the *electron* (e^-, $m_e = 511$ keV, 1 keV = 1000 eV, 1 eV = 1.60×10^{-19} Joules), *muon* (μ, $m_\mu = 107$ MeV), and *tau particle* (τ, $m_\tau = 1784$ MeV), each with a negative charge; their respective neutrinos: *electron neutrino* (ν_e, $m_{\nu-e} < 30$ eV), *muon neutrino* (ν_μ, $m_{\nu-\mu} < 0.5$ MeV), and *tau neutrino* (ν_τ, $m_{\nu-\tau} < 250$ MeV), each with no charge; and the antiparticles of each: e^+ (called a *positron*), $\overline{\mu}, \overline{\tau}, \overline{\nu_e}, \overline{\nu_\mu}$, and $\overline{\nu_\tau}$. These particles do **<u>not</u>** participate in the strong interactions. All leptons have spin of 1/2.

ii) **Mesons** are particles of intermediate mass that are made of quark-antiquark pairs and include *pions*, *kaons*, and η-*particles.* All are unstable and decay via weak or E/M interactions. All mesons have either 0 or integer spin.

iii) **Baryons** (*heavy* particles) include the nucleons n (*neutrons* — neutral particles) and p (*protons* — positively charged) and the more massive *hyperons* (*i.e.*, Λ, Σ, Ξ, and Ω). Baryons are composed of a triplet of quarks. Each baryon has an antibaryon associated with it and has a spin of either 1/2 or 3/2.

b) **Field particles**: These particles mediate the 4 natural forces as mentioned above: **gluons**, **photons**, **weakons**, and **gravitons**. These are the *energy* particles.

4. From the above list of elementary particles, there seems to be only 2 types of basic particles: *leptons* which do not obey the strong force and *quarks* which do obey the strong force. There are 6 types of leptons (as describe above). As such, it was theorized and later observed, 6 types of quarks (and an additional 6 antiquarks) must exist:

a) **Up** (u) quark has a rest energy of 360 MeV (1 MeV = 10^6 eV) and a charge of $+\frac{2}{3}\,e$.

b) **Down** (d) quark has a rest energy of 360 MeV and a charge of $-\frac{1}{3}\,e$.

c) **Charmed** (c) quark has a rest energy of 1500 MeV and a charge of $+\frac{2}{3}\,e$.

d) **Strange** (s) quark has a rest energy of 540 MeV and a charge of $-\frac{1}{3}\,e$.

e) **Top** (t) quark has a rest energy of 170 GeV (1 GeV = 10^9 eV) and a charge of $+\frac{2}{3}\,e$.

f) **Bottom** (b) quark has a rest energy of 5 GeV and a charge of $-\frac{1}{3}\,e$.

5. Note that a proton is composed of 2 u and a d quark and a neutron composed of an u and 2 d quarks.

6. The theory on how quarks interact with each other is called **quantum chromodynamics**. One interesting result of this theory is that quarks cannot exist in isolation, they must always travel in groups of 2 to 3 quarks.

7. There are 2 addition terms that are used to describe particles — terms that describe the *spin* of a particle:

a) In quantum mechanics, a system of identical particles 1, 2, 3, ... is described by a **wave function**, which describes the spin of the particle.

b) A wave function must be either **symmetrical** (even) or **antisymmetrical** (odd) with respect to the interchange of coordinates of any pair of identical particles.

c) If symmetrical, the particles are called **bosons** and have zero or integer (*i.e.*, 0, 1, 2, 3, ...) spins.

d) If antisymmetrical, the particles are called **fermions** and have half-integer (*i.e.*, $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, ...$) spins.

e) An antisymmetrical wave function must vanish as 2 identical particles approach each other. As a result, 2 fermions in the same quantum state exhibit a strong mutual repulsion $\Longrightarrow$ **Pauli Exclusion Principle**.

f) No such restrictions exist for bosons.

g) Leptons and baryons are fermions.

h) Mesons and field particles (*i.e.*, photons) are bosons.

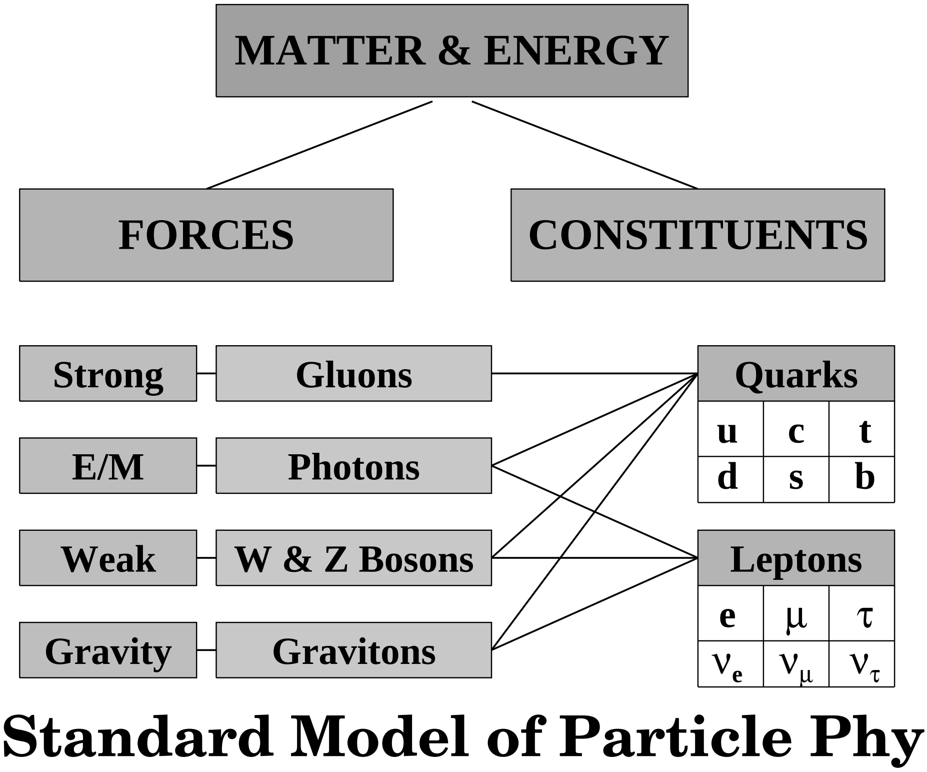

Figure XI–7: The Standard Model is the current best description of the subatomic world.

D. History of the Universe

1. Singularity, the Big Bang Itself!

$$t = 0, \quad D = 0, \quad \rho = \rho_{\rm rad} \rightarrow \infty, \quad T = T_{\rm rad} \rightarrow \infty \ .$$

a) If the Universe is closed, then a finite amount of mass-energy is located in a zero volume (like a black hole singularity).

b) If the Universe is open or flat, then the Universe has an infinite total amount of mass-energy located in an infinite volume at this stage.

c) We currently have no physics that can describe the history and events occurring in the Universe at this point. Perhaps if quantum mechanics and general relativity are ever combined (*i.e.*, **quantum gravity**) (see Figure XI-

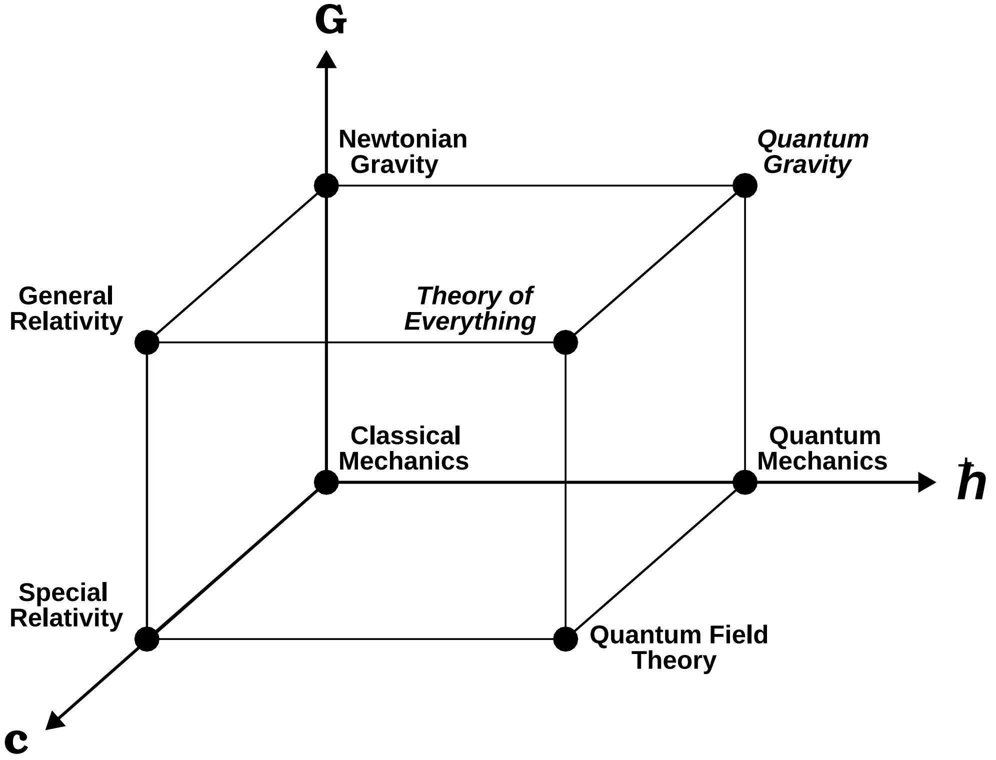

Figure XI–8: The relationship of the various theories of the natural force with respect to the fundamental physical constants of the Universe. Note that those "theories" (actually hypotheses) in italics have not yet been confirmed.

8), we will have a physical theory that can describe the Universe here and explain why the Big Bang ever occurred.

d) In the header lists for each of these eras, t represents time since the Big Bang, D the diameter of the Universe at time t, ρ is the mass-energy density, T is the temperature, and later, z corresponds to the redshift. Each of these values are listed at the beginning and ending of each era.

2. Quantum Era

$$\begin{aligned} 0 < t < 10^{-43}\ \text{sec} &= t_{\rm P} = \text{ Planck Time}, \\ 0 < D < 10^{-33}\ \text{cm} &= \ell_{\rm P} = \text{ Planck Length}, \\ \rho = \rho_{\rm rad} > 10^{90}\ \text{gm/cm}^3, &\qquad T = T_{\rm rad} > 10^{32}\ \text{K}\ . \end{aligned}$$

a) The earliest time that can be addressed by current physical theory is the **Planck time**:

$$t_{\rm P} \equiv \sqrt{\frac{\hbar G}{c^5}} = 5.39 \times 10^{-44}~{\rm s}~, \qquad \text{(XI-5)}$$

where $\hbar$ is the angular Planck's constant ($\hbar = h/2\pi$).

b) In a Planck time, the speed of light crosses a distance called the **Planck length**:

$$\ell_{\rm P} = t_{\rm P}\, c \equiv \sqrt{\frac{\hbar G}{c^3}} = 1.62 \times 10^{-33}~{\rm cm}~. \qquad \text{(XI-6)}$$

c) The uncertainty principle from quantum mechanics tells us that the uncertainty in a particle's momentum times the uncertainty in position must be greater that $\hbar$. If we use the Schwarzschild radius of the early Universe as the position uncertainty, we can use conservation of energy to describe the **Planck mass**:

$$m_{\rm P} \equiv \sqrt{\frac{\hbar c}{G}} = 2.18 \times 10^{-5}~{\rm gm}~. \qquad \text{(XI-7)}$$

The Planck mass can be interpreted as the minimum mass that any primordial black holes can have if created in the Big Bang.

d) Physics will not be understood in this Quantum Era until quantum effects are successfully included in gravity as described previously.

e) During this time, it is speculated that all forces, including gravity, act as one force $\Longrightarrow$ the **Theory of Everything** (see Figure XI-8).

3. GUT (Grand Unified Theory) Era

$$\begin{aligned} 10^{-43}\ \text{sec} &< \quad t \quad < 10^{-34}\ \text{sec} \\ 10^{-33}\ \text{cm} &< \quad D \quad < 10^{-24}\ \text{cm} \\ 10^{90}\ \text{gm/cm}^3 &< \quad \rho_{\text{rad}} \quad < 10^{72}\ \text{gm/cm}^3 \\ 10^{32}\ \text{K} &< \quad T \quad < 10^{27}\ \text{K}\ . \end{aligned}$$

a) At the beginning of this era, gravity breaks from the unified force, following the equations of general relativity, and gets progressively weaker (see Figure XI-9). This **symmetry breaking** acts like a phase transition of the Universe.

b) During this time, the strong, weak, and electromagnetic forces act as one as described by the **Grand Unified Theory**.

c) Temperature is so high that only field particles exist: gravitons, weakons (*i.e.*, intermediate vector bosons), photons, and gluons.

d) At the end of this era, the strong force decouples from the **electroweak** force $\Longrightarrow$ the Universe goes through another phase transition.

4. Inflationary Era

$$\begin{aligned} 10^{-34}\ \text{sec} &< \quad t \quad < 10^{-32}\ \text{sec} \\ 10^{-24}\ \text{cm} &< \quad D \quad < 330\ \text{cm} \\ 10^{72}\ \text{gm/cm}^3 &< \quad \rho_{\text{rad}} \quad < 10^{37}\ \text{gm/cm}^3 \\ 10^{27}\ \text{K} &< \quad T \quad < 10^{18}\ \text{K}\ . \end{aligned}$$

a) The electroweak-decoupling phase transition causes the Universe to expand exponentially from 10^{-24} cm to 330 cm (10^{28} cm today).

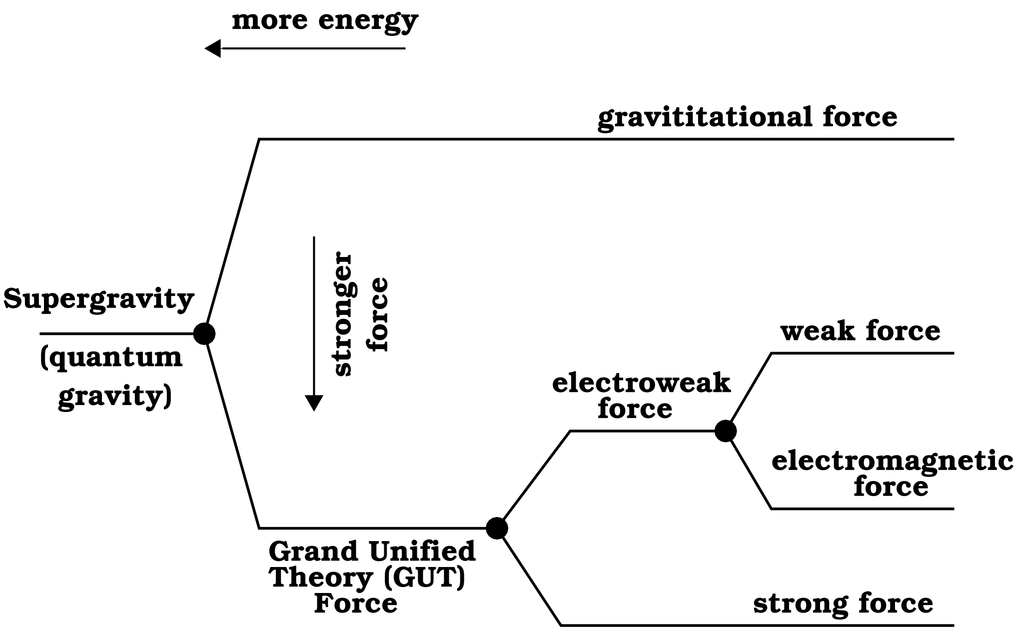

Figure XI–9: The 'Theory' of Everything will describe the four natural forces as one force at very high energies (that is, early in the Universe). The four combined forces are called **unification** and are said to have symmetry. As it expands, the Universe cools (*i.e.*, looses energy) and at certain temperatures, forces start to decouple. Each *symmetry breaking* of the natural forces of the Universe, shown as 'dots' in this figure, correspond to the Universe changing its state. The decoupling of the GUT Force causes the Universe to expand exponentially instead of the standard linear expansion seen during the other epochs.

b) During this time, all baryonic matter is created from the primeval *soup* of field particles $\Longrightarrow$ individual **quarks** and **antiquarks** are made $\Longrightarrow$ matter (and antimatter) arise from the field energy particles via $E = mc^2$.

i) Field particles all have integer spins $\Longrightarrow$ they are bosons.

ii) The GUT predicts that baryon number conservation and charge & parity (CP) conservation can be violated occasionally. In particle physics, *parity* is defined as the symmetry of behavior in an interaction of a subatomic particle with that of its mirror image.

iii) These CP violations can cause slight asymmetries in decay rates of a given boson decaying to more stable particles:

- The *kaon* K can decay to a *pion* π via either

$$\begin{aligned} K &\rightarrow \pi^- + e^+ + \nu_e \\ K &\rightarrow \pi^+ + e^- + \overline{\nu}_e \ . \end{aligned}$$

- The first of these two reactions occurs slightly (but measurably) more frequently than the second.

- As such, it is possible to get slight asymmetries between matter and antimatter over time as these particles are made out of the field particle soup.

c) During this time, the temperatures are too high for the strong force to connect the quarks together to make baryons and anti-baryons.

d) Due to CP violation, for every 30 million antiquarks, there are 30 million + 1 quarks by the end of this era.

e) The Universe resumes a linear expansion at the end of this era.

5. Quark Era

$$\begin{aligned}
10^{-32}\text{ sec} &< \quad t \quad < 10^{-6}\text{ sec} \\
330\text{ cm} &< \quad D \quad < 10^{9}\text{ cm } = 4D_{\oplus} \\
10^{37}\text{ gm/cm}^3 &< \quad \rho_{\rm rad} \quad < 10^{17}\text{ gm/cm}^3 \\
10^{18}\text{ K} &< \quad T \quad < 10^{13}\text{ K} .
\end{aligned}$$

a) Forces between quarks act strangely: The farther away they get from each other, the stronger the force exerted (opposite of the direction of gravity). At the beginning of this era, the temperature is so high that quark motions can overcome this force and hence are <u>not</u> bound with each other.

b) At $t = 10^{-12}$ sec, $T = 10^{15}$ K, $\rho = 10^{24}$ gm/cm^3, the electromagnetic and weak forces decouple $\Longrightarrow$ when this occurs, leptons start to form.

c) This era ends when the temperature is cool enough for quarks to form bound states ($T = 10^{13}$ K, $\rho = 10^{17}$ gm/cm^3) and become hadrons.

6. Hadronic Era

$$\begin{aligned} 10^{-6}\text{ sec} &< t < 1\text{ sec} \\ 10^{9}\text{ cm} &< D < 10^{14}\text{ cm} = 15\text{ AU} \\ 10^{17}\text{ gm/cm}^3 &< \rho_{\text{rad}} < 10^{5}\text{ gm/cm}^3 \\ 10^{13}\text{ K} &< T < 10^{10}\text{ K}\,. \end{aligned}$$

a) During this time, proton-antiproton pairs constantly annihilate and reform $\Longrightarrow$ hadrons are said to be in thermal equilibrium with photons (*i.e.*, the radiation field).

b) At the end of this era, $T = 10^{10}$ K, $\rho = 10^5$ gm/cm^3, the energy density is too low to produce proton-antiproton pairs. These particles annihilate one last time — <u>except</u> there is a *slight* asymmetry between protons and antiprotons, for every 10^9 antiprotons there are $10^9 + 1$ protons (once again, due to CP violation). The remaining protons have nothing to annihilate with and remain.

7. Lepton Era

$$\begin{aligned} 1\text{ sec} &< t < 1\text{ min} \\ 10^{14}\text{ cm} &< D < 10^{15}\text{ cm} = 150\text{ AU} \\ 10^{5}\text{ gm/cm}^3 &< \rho_{\text{rad}} < 10^{4}\text{ gm/cm}^3 \\ 10^{10}\text{ K} &< T < 6\times 10^{9}\text{ K}\,. \end{aligned}$$

a) Electron-positron pairs are still in equilibrium.

b) At the end of this era, $T = 6 \times 10^9$ K, $\rho = 10^4$ gm/cm^3, the energy density becomes too low to make new electron-positron pairs $\Longrightarrow$ an excess of electrons is left over due to asymmetries in the intermediate vector boson decays.

8. Nucleosynthesis Era

$$\begin{aligned} 1\ \text{min} &< \quad t &&< 3\ \text{min} \\ 10^{15}\ \text{cm} &< \quad D &&< 10^{19}\ \text{cm}\ = 10\ \text{ly} \\ 10^{4}\ \text{gm/cm}^3 &< \quad \rho_{\text{rad}} &&< 10^{-8}\ \text{gm/cm}^3 \\ 6 \times 10^{9}\ \text{K} &< \quad T &&< 10^{7}\ \text{K}\ . \end{aligned}$$

a) Temperatures and densities exist such that H fuses into ^{2}H (deuterium).

$$\begin{aligned} {}^1\text{H} + {}^1\text{H} &\longrightarrow {}^2\text{H} + e^+ + \nu \\ n + {}^1\text{H} &\longrightarrow {}^2\text{H} + \gamma\ . \end{aligned}$$

b) Temperatures are too high to fuse ^{2}H $\Longrightarrow$ it photodissociates as fast as it forms. He (helium) cannot be created as a result of this, even though the temperature is high enough $\Longrightarrow$ the **deuterium bottleneck**.

c) When $T < 10^9$ K ($t \approx 100$ sec, 1.5 min), ^{2}H no longer dissociates and fuses immediately into He $\Longrightarrow$ however, the Universe is now too cool to fuse He → C (carbon) and O (oxygen) via the triple-α process (see page VI-10 of these course notes).

d) At $t = 3$ min, $T < 10^7$ K, $\rho < 10^{-8}$ gm/cm^3, and He production ceases. Since the last stages of the p-p chain are not as efficient as the first stage, an excess number of ^{2}H (deuterium) is left over (and some ^{7}Li [lithium-7] from the branch reactions of the full p-p chain) $\Longrightarrow$ the amount left over depends critically on the density of the Universe at that time. Since deuterium and lithium-7 are easily destroyed in the interior of stars, all of the ^{2}H and ^{7}Li we currently see in the Universe arose during this Nucleosynthesis Era.

e) The future of the Universe is now set $\Longrightarrow$ all within the first 3 minutes!

9. Radiation Era

$$\begin{aligned} 3 \text{ min} &< t < 10{,}000 \text{ yr} \\ 10^9 &< z < 2200 \\ 10^{19} \text{ cm} &< D < 10^{21} \text{ cm} = 1000 \text{ ly} = 300 \text{ pc} \\ 10^{-8} \text{ gm/cm}^3 &< \rho < 10^{-15} \text{ gm/cm}^3 \\ 10^7 \text{ K} &< T < 10^5 \text{ K} . \end{aligned}$$

a) In this era, $\rho_{\rm rad} > \rho_{\rm matter}$.

b) The temperature is still greater than 10^5 K which keeps hydrogen ionized.

c) Since H is ionized, there are an abundance of free electrons which effectively *blocks* the flow of radiation (*i.e.*, photons) $\Longrightarrow$ Compton scattering and Thompson scattering.

d) The Universe is completely *opaque* during this time.

e) At the end of this era, $\rho_{\rm m} = \rho_{\rm rad}$.

10. Matter Era

$$\begin{aligned} 1000 \text{ yr} &< t < \text{ present } = 13.7 \text{ Gyr} \\ 2200 &< z < 0 \\ 10^{21} \text{ cm} &< D < 10^{28} \text{ cm} = 13.7 \text{ Gly} = 4.2 \text{ Gpc} \\ 10^{-15} \text{ gm/cm}^3 &< \rho < 3 \times 10^{-30} \text{ gm/cm}^3 \\ 10^5 \text{ K} &< T < 2.7 \text{ K} . \end{aligned}$$

a) Here we are assuming that *present* is at $t = 13.7 \times 10^9$ (13.7 billion) years.

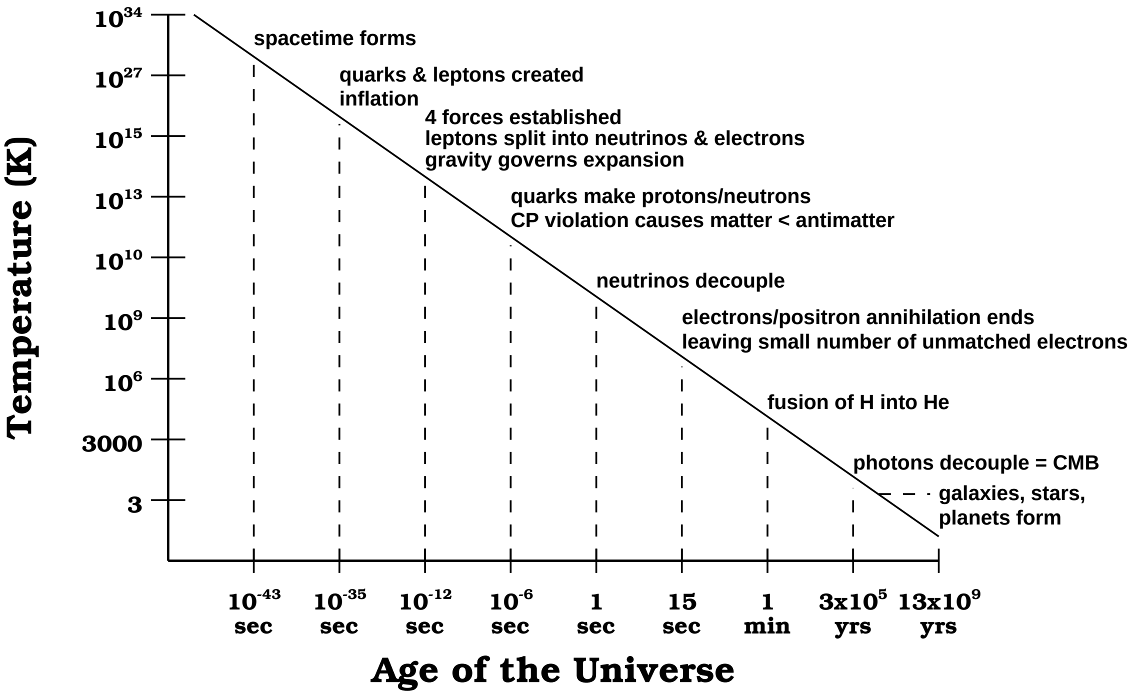

Figure XI–10: Graphical representation of the history of the Universe.

b) Matter begins to dominate radiation in this era: $\rho_{\rm matter} > \rho_{\rm rad}$.

c) H (hydrogen) becomes <u>completely</u> neutral when $T < 3000$ K ($t = 300{,}000$ years, $z = 1100$) $\Longrightarrow$ the Universe becomes transparent to light since the opacity from electron scattering drops to zero!

  i) We see this epoch today as the 2.7 K background radiation $\Longrightarrow$ visible light when emitted at $z = 1100$, redshifted today ($z = 0$) to microwave radiation.

  ii) This time is called the **recombination time** of the Universe.

  iii) This is what we are seeing when we observe the 2.7 K background.

d) Inhomogeneities in the matter begin to grow due to gravitational instabilities just after recombination.

  i) The densest parts of these inhomogeneities quickly collapse down to form supermassive black holes.

  ii) Hydrogen and helium created in the Big Bang start to accumulate in the vicinity of these supermassive black holes forming **protogalaxies**.

  iii) During this time after the recombination but before the first stars light up, the Universe is dark at visible wavelengths.

e) Galaxies begin to "light-up" as this accumulating hydrogen and helium reach high enough densities for star formation to begin.

  i) It is at this time that the Population III stars (*i.e.*, no metalicity) begin to form in earnest from the IGM (intergalactic medium) and ISM (interstellar medium).

  ii) This occurs at approximately $z = 20, t = 1 \times 10^8$ years after the Big Bang.

f) Galaxies begin to cluster at $z \approx 10, t = 3 \times 10^8$ years.

g) The first Population II (low metalicity) stars form in our Galaxy out of material expelled from the Population III stars at $z \approx 9, t = 4 \times 10^8$ years after the Big Bang.

h) Quasars become active and Population II stellar formation rates begin to drop in the Milky Way at $z \approx 6, t = 6 \times 10^8$ years.

i) Population I stars begin to form in Milky Way at $z \approx 1, t = 4 \times 10^9$ years.

j) The Sun and Solar System form when $z = 0.02$ and $t = 9 \times 10^9$ years after the Big Bang.

k) As the matter density of the University continues to drop as the Universe expands, the gravitational force of all the galaxies pulling on each other continues to weaken. The *dark energy* force, however, remains constant over time since it is associated with the cosmological <u>constant</u>.

  i) At $t = 10 \times 10^9$ years, the force from this dark energy exceeds the gravitational force of the entire Universe for the first time.

  ii) At this point, the expansion of the Universe goes from a "decelerating" rate to an "accelerating" rate.

  iii) Hence the Universe become dark energy dominated some 10 billion years after the Big Bang.

l) Life begins on Earth around this same time at $t = 10 \times 10^9$ years after the Big Bang, and the first primates arise at $t = 13.696 \times 10^9$ years after the Big Bang.

m) Presently the Universe is at of age of 13.7×10^9 (13.7 billion) years (*i.e.*, $z = 0$).