Cosmology and particle physics

Lecture notes

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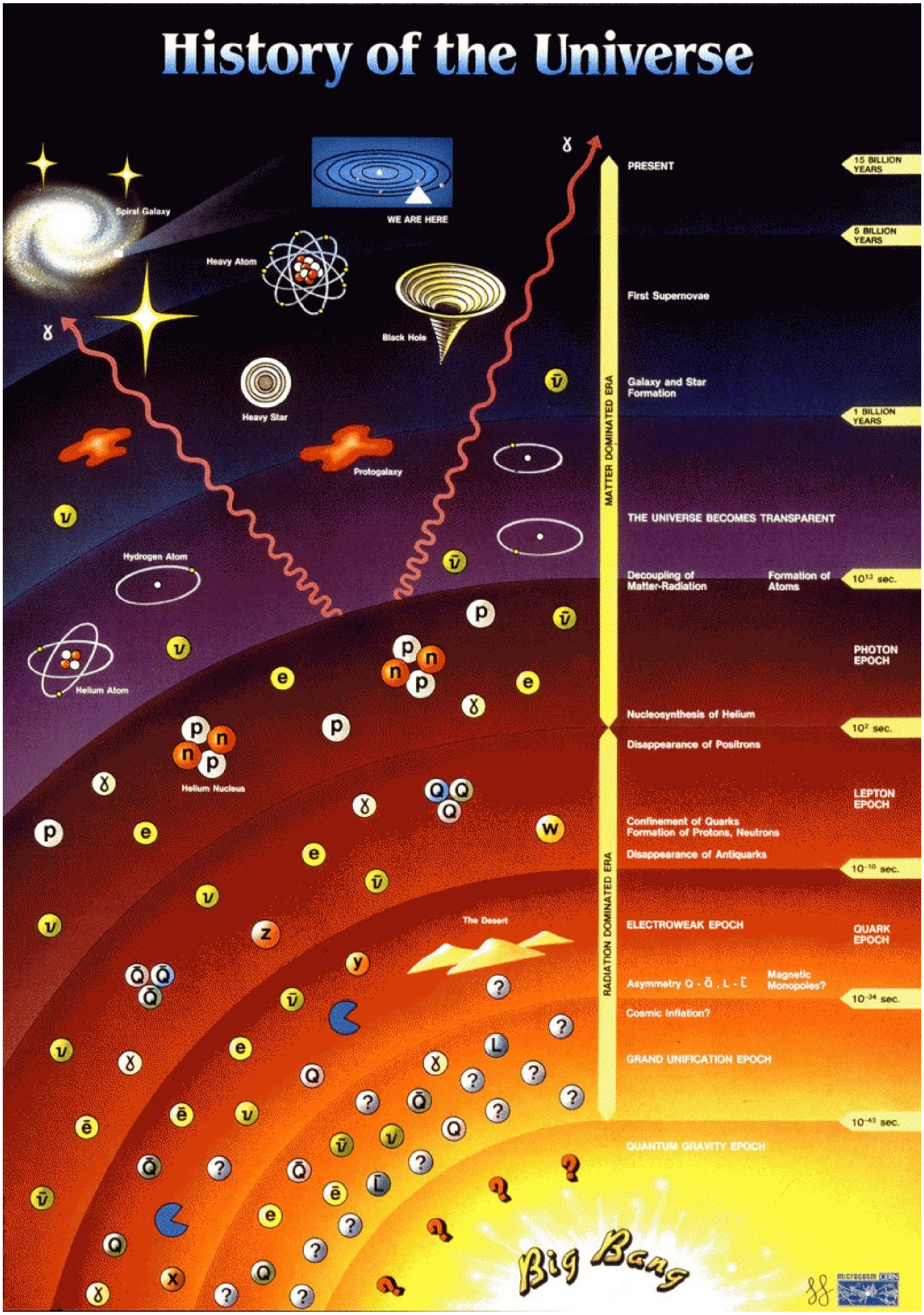
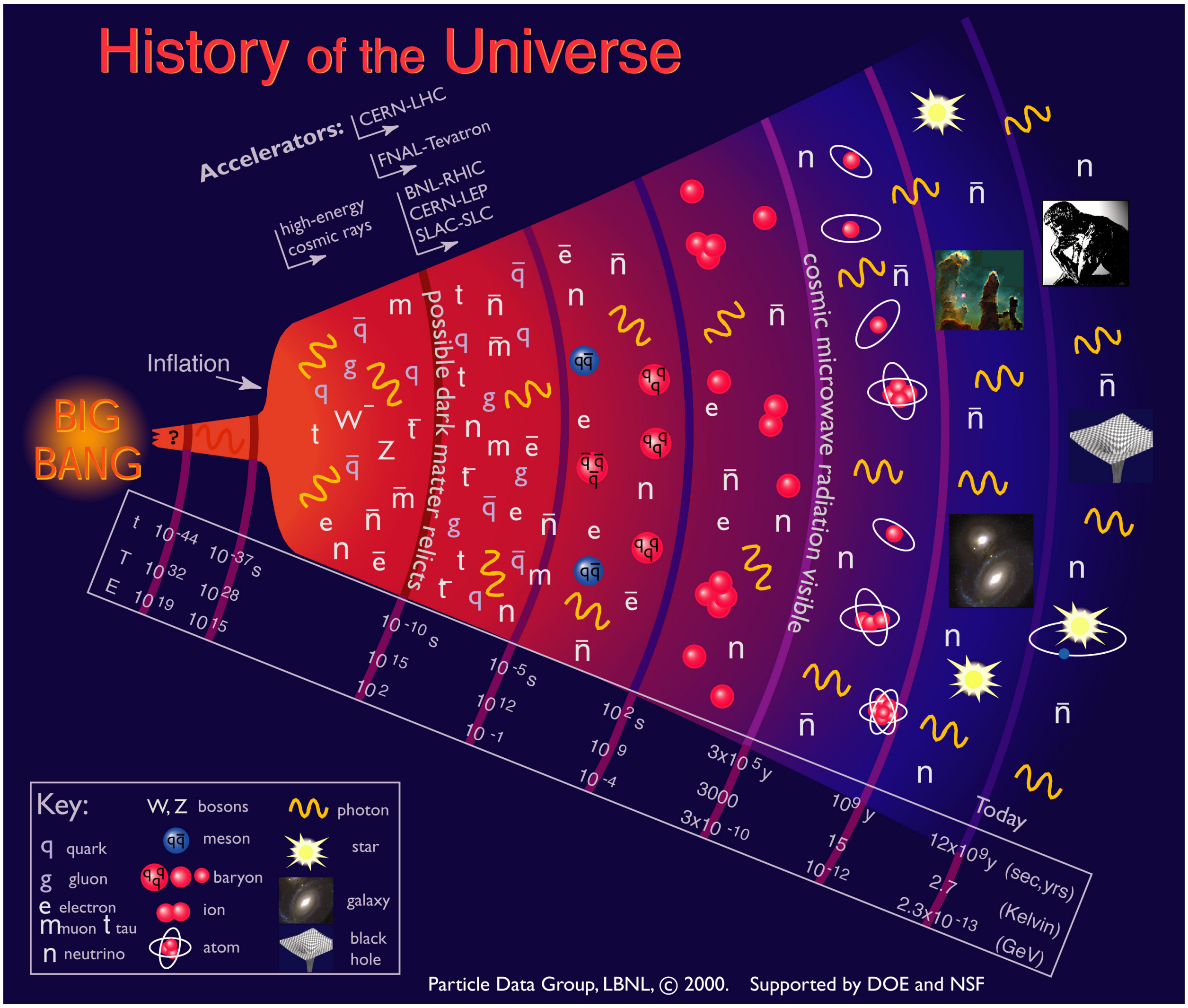
Lecture 12 Summary: Our universe

In this lecture we quickly summarize the important events during the evolution of our universe from its beginning until today. While this lecture contains nothing new, it provides a concise time-line of our universe.

Event	Time	Redshift	Temperature
Planck era	$10^{-43}s$	?	$2\times10^{18}GeV$
GUT scale	$10^{-40}s$	?	$10^{16}GeV$
Inflation	unclear: $10^{-38}-10^{-14}s$?	?	-
Baryogenesis	?	?	?
EW phase transition	$2\times10^{-11}s$	10^{15}	$100GeV$
QCD phase transition	$2\times10^{-5}s$	10^{12}	$150MeV$
Dark matter freeze-out	?	?	?
Neutrino decoupling	$1s$	6×10^{9}	$1MeV$
Electron-positron annihilation	$6s$	2×10^{9}	$500keV$
Big bang nucleosynthesis	$3min$	4×10^{8}	$100keV$
Matter-radiation equality	$60\times10^{3}yrs$	3400	$.75eV$
Recombination	$260-380\times10^{3}yrs$	1100-1400	$.26-.33eV$
CMB	$380\times10^{3}yrs$	1100	$.26eV$
Reionization (first stars)	$200\times10^{6}yrs$	19	$4.7meV$
Accelerated expansion starts	$7.6\times10^{9}yrs$	.65	$.4meV$
Formation of solar system	$9.2\times10^{9}yrs$	.42	$.34meV$
Dark energy-matter equality	$10.2\times10^{9}yrs$	.31	$.31meV$
Today	$13.8\times10^{9}yrs$	0	$.24meV$


History of the Universe
Spiral Galaxy
WE ARE HERE
Heavy Atom
Black Hole
Heavy Star
Protogalaxy
Hydrogen Atom
Helium Atom
Helium Nucleus
The Desert
Big Bang
PRESENT
First Supernovae
Galaxy and Star Formation
THE UNIVERSE BECOMES TRANSPARENT
Decoupling of Matter-Radiation
Formation of Atoms
Nucleosynthesis of Helium
Disappearance of Positrons
Confinement of Quarks Formation of Protons, Neutrons
Disappearance of Antiquarks
ELECTROWEAK EPOCH
Asymmetry Q - Q̄ , L - L̄
Magnetic Monopoles?
Cosmic Inflation?
GRAND UNIFICATION EPOCH
QUANTUM GRAVITY EPOCH
MATTER DOMINATED ERA
RADIATION DOMINATED ERA
15 BILLION YEARS
5 BILLION YEARS
1 BILLION YEARS
10¹³ sec.
PHOTON EPOCH
10² sec.
LEPTON EPOCH
10⁻¹⁰ sec.
QUARK EPOCH
10⁻³⁴ sec.
10⁻⁴³ sec.



The beginning (Planck era): General relativity inevitably breaks down near the Planck scale. At this point we need a UV complete theory of quantum gravity. Our best contender, string theory, is currently not well enough understood to understand a space-like singularity like the big bang. Even if we would get a theoretical handle on such a singularity, it would be very hard to test this theory since inflation is very successful at erasing any information about the universe before inflation started.

GUT scale: The interaction strengths of the strong, weak and electromagnetic forces are functions of the energy scale. At the grand unified theory (GUT) energy scale of $10^{16} GeV$ all three are almost the same. Many people believe that the three forces get unified to a single grand unified force, since it is non-trivial that three lines intersect in a point. Breaking of this single force into the three forces we observe can lead to relics like magnetic monopoles that could overclose the universe ($\Omega \gg 1$). A period of inflation with a reheating temperature below the GUT scale would solve this problem.

Inflation: Inflation is a period of exponential expansion of our universe. The lower bound on the expansion of the scale factor during inflation is 50-60 e-folds, i.e. $a_f/a_i \geq e^{50} - e^{60}$. Such a period solves the horizon and flatness problem but more interestingly it provides the inhomogeneities needed to explain the structure in our universe. The inflaton undergoes quantum fluctuations that get stretched during the rapid expansion and after inflation get converted into small inhomogeneities. These inhomogeneities are then being enhanced due to the gravitational attraction. So slightly denser regions will become galaxies and galaxy clusters while less dense region will become emptier and emptier. Thus quantum fluctuations during inflation provide the seeds for our galaxies!

Baryogenesis: As we discussed in lecture 5, there is an asymmetry between baryons and anti-baryons that cannot be explained by the standard model of particle physics. Thus at energies above $1TeV$ there must be some new physics that generates this asymmetry. While there are many different theoretical ideas, there is no experimental test of any of these so we cannot associate a time to baryogenesis. Since the observed universe is neutral under the electric charge, there must be a similar asymmetry between electrons and positrons so that after their annihilation we are left with one electron for each proton.

Electroweak-phase transition: During this phase transition particles get their mass due to the so called Higgs effect. Once the standard model particles are massive they start to drop out of equilibrium whenever the temperature of the universe (i.e. the thermal bath) becomes smaller than their mass. Then the particles start to annihilate with their anti-particles and their number densities decrease exponentially. The remaining matter in our observed universe is due to the matter-anti-matter asymmetry mentioned above.

QCD phase transition: The strong force is weaker at higher energies (temperatures) and becomes stronger and stronger during the cooling of the universe. Around $150MeV$ the strong force is so strong that free gluons and quarks cannot exist anymore and all the quarks are bound into so called baryons and mesons. These are bound states that are neutral under the strong force. The lightest baryons are the familiar proton and neutron. There are also heavier baryons and mesons that can be lighter than the proton and neutron but all of these are unstable and quickly decay. So a little bit after the QCD phase transition we are left with essentially only protons and neutrons that are the building blocks for the atomic nuclei.

Dark matter freeze-out: If we assume that the unknown dark matter (DM) is a very weakly interacting, massive particle that was initially in equilibrium with the standard model particles, then it should freeze-out around or before the neutrino decoupling to give the correct relic abundance that we observe today, i.e. to provide a contribution to the energy density today that is roughly five times as large as the contribution of the regular matter (RM) ($\Omega_{DM} \approx .25 \approx 5\Omega_{RM}$).

Neutrino decoupling: Around $1MeV$ the weak interaction becomes so weak that particles that are only charged under the weak force, i.e. the neutrinos, decouple from the thermal plasma. These neutrinos, similarly to the photons in the CMB, give rise to a cosmic neutrino background that is slightly colder than the CMB and very difficult to observe directly. At the time of decoupling the three neutrinos are still relativistic and during the cooling of the universe they become non-relativistic whenever their temperature becomes smaller than their respective mass. Note however that this does not mean that their number density will decay exponentially, since the neutrinos are decoupled from themselves so that they cannot annihilate with each other.

Electron-positron annihilation: Around $T \sim m_e \approx 511keV$ the electrons and positrons become non-relativistic and transfer their energy and entropy into the photons only (since the neutrinos are decoupled already). This slows down the decrease in the temperature of the photons a little bit so that the photons today have a temperature that is a little bit larger than the neutrino background.

Big bang nucleosynthesis: One of the greatest successes of the big bang cosmology is that it correctly predicts the observed abundance of elements in our universe. Using nuclear physics, we can predict the amounts of different elements in the early universe and these predictions agree with what we observe, in particular besides traces of heavier elements our universe consists of 93% Hydrogen and 7% Helium. Any kind of new physics that can appear beyond the standard model is severely constrained by this success.

Recombination: Once the average energy of the photons drops below $.33eV$ the tail of high energy photons is sufficiently small to allow for neutral atoms to form. This process in which electrons and protons combine takes roughly 100,000 years and at its end the universe is filled with clouds of neutral atoms and the cosmic microwave background.

The cosmic microwave background (CMB): Once the electrons and nuclei combine into neutral atoms, the photons can stream freely until today. The observation of this cosmic microwave background does not only tell us about the universe 380,000 years after the big bang but the incredible homogeneity of the CMB also strongly motivates a phase of inflation in our very early universe. The small deviations from homogeneity in the CMB photons we observe together with their polarization provide detailed information about this period of inflation.

Reionization (first stars): The formation of the first stars leads to the release of large amounts of energy from the nuclear fusion in the stars. This energy is emitted from the stars via photons and these photons reionize the neutral atoms in the universe that are in large clouds and which will provide the fuel for future generations of stars. (Star formation should end around 10^{14} years from now, so there is still plenty of fuel out there.) The nuclear fusion in the first stars also creates the heavy elements that we observe in our universe and that were not created during big bang nucleosynthesis.

Accelerated expansion starts: The standard forms of energy density like radiation and non-relativistic matter lead to a deceleration of the expansion of our universe, i.e. $\ddot{a}(t) < 0$. This means that since the end of inflation our universe is expanding but at a decelerating rate. Due to the presence of a positive cosmological constant our universe started to expand at an accelerating rate roughly 6.2 Gyrs ago. Since matter gets diluted away during the further expansion of our universe, while the energy density due to the cosmological constant remains constant our universe is asymptotically approaching a dS phase in its future.

Formation of the solar system: As a reference point I included the age of the solar system which formed around $4.6Gyrs$ ago. Our milky way contains much older stars and its age is believed to be around $13.2Gyrs$. The presence of older stars in our vicinity is required in order to explain the abundance of heavy elements in our solar system. These heavier elements are created via nuclear fusion in the first stars and then released during supernovae.

Dark energy-matter equality: Our current universe consists of roughly 70% dark energy and 30% matter (out of which roughly 25% is dark matter and 5% is regular matter like Hydrogen and Helium). Since matter gets diluted away during the expansion of the universe while the energy density of the cosmological constant does not, this means that in the not too distant past, roughly $3.6Gyrs$ ago, the energy density of the universe was consisting to 50% of dark energy and to 50% of matter. Note that the accelerated expansion due to the cosmological constant did start earlier.

Today: The age of our universe is roughly $13.8Gyrs$ where the last digit can still change due to the uncertainty in the Hubble parameter. However, there are a variety of different experiments that all place mutually consistent bounds on the age of the universe so that the age of our universe is undoubtedly finite.