16.0: The Early Universe Introduction

Video Transcript

> ***Recreating The Big Bang: Transcript***
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> *The Universe came into existence 13.7 billion years ago with the event known as the Big Bang. We have been able to see back, close to the beginning, using telescopes to capture distant light emitted billions of years ago. The famous Hubble Space Telescope has allowed us to look back when galaxies were still in the process of forming.*
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> *The WMAP provided us with an amazing view of the cosmic microwave background – the afterglow of the Big Bang. Before this point, the Universe was too hot and light was unable to shine through the dense fog of charged particles. This prevents telescopes from being able to see beyond this point. However, there is a way to recreate the conditions of this early Universe right here on Earth.*
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> *The conditions of the early Universe were of extreme heat and energy, which lead to the creation of strange forms of matter and physics. For decades, particle physicists have been recreating these early conditions with particle accelerators, smashing particles together to create similar levels of heat and energy. Particle detectors are then employed to capture these events to help us learn more about what the Universe was like in these early times.*
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> *ATLAS is such a detector at the Large Hadron Collider. Late in 2009, the LHC and the ATLAS detector broke world records by creating and detecting the highest energy collisions ever made. In the years to come, it will reach its full capacity and push to even higher energies and further back in time. ATLAS will be discovering new kinds of particles, such as the Higgs, and unlocking new realms of physics that may include new dimensions of space and particles of dark matter.*
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> *This frontier of knowledge will continue to be pushed to help us learn more about the origins of our Universe and what happened a fraction of a second after the Big Bang.*

Credit: ATLAS Experiment/CERN

By studying large-scale structure and cosmic microwave background, we have traced the history of the Universe all the way back in time to when the light left the farthest objects we can see with our best telescopes. We saw that there is a limit to our lookback time, because until about 380,000 years after the Universe began it was opaque. The video shows that we can investigate much earlier times by reproducing their conditions on a tiny scale here on Earth; for this we use huge particle accelerators.

The very early Universe was extremely hot and dense. Remember that temperature is just a measure of the kinetic energy of particles, so it is a measure of their speed. Particle colliders like the Large Hadron Collider (Figure 16.0.1) can use pulsing electromagnetic fields to accelerate charged particles, usually protons or electrons, to close to the speed of light. Such speeds correspond to those typical of the entire Universe around 10^{-14} seconds after the Universe came into existence. At that time the temperature was 100 million billion (10^{17}) kelvin! Although we only look at the characteristics of a few particles at a time using our colliders, we are confident that we can use what they show us to understand the Universe at early times. Complex structures like molecules and atoms cannot exist at high temperatures, so the physics of the early Universe would have been very simple. Collisions between elementary particles would have dominated - a situation analogous to what we can study with accelerators.

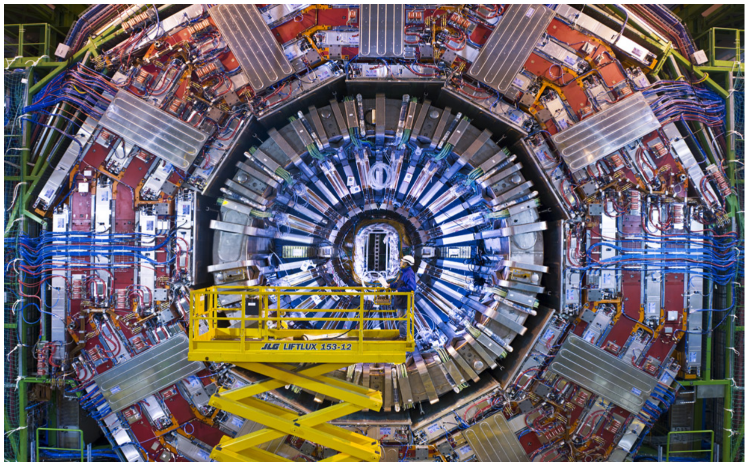

Figure 16.0.1: The CMS (Compact Muon Solenoid) experiment at the European Organization for Nuclear Research (CERN) near Geneva, Switzerland. CMS is an experiment at the Large Hadron Collider (LHC), currently the most powerful particle accelerator in the world. Credit: CERN/Maximillien Brice

Going Further 14.1: Studying the Early Universe Using Particle Colliders

There are two basic kinds of charged particle accelerators. One kind was so common a few years ago that many ordinary people owned them! The cathode ray tube of old televisions is an example of an electrostatic accelerator. It uses the force from an electric field to accelerate electrons. The electrons then hit a screen and release the photons that we see.

Much higher energies can be achieved using oscillating electric fields. In these machines, the charged particles are accelerated for a short distance and then the electric field changes direction to give them an extra kick. As they pass through a hole in a plate, the electric polarity is switched so that the plate repels them and they are accelerated toward the next plate. In order to accelerate particles to near the speed of light, microwave cavities are used instead of simple plates, because the oscillation rate of the electric fields becomes higher in higher energy machines.

Oscillating field accelerators have two subtypes. Linear accelerators send their particles in a straight line. The particle paths can be up to several kilometers long. Circular accelerators, called synchrotrons, curve the particle tracks using powerful magnets. Synchrotrons take their name from the fact that the electromagnetic field oscillations must be synchronized to the particle orbital motions so that the particles receive a boost in energy each time they come around their circular path.

Only the largest machines are used for particle physics research; less powerful versions have many medical and industrial applications. The goal of the research machines is to produce the simplest kinds of interactions at the highest possible energies by colliding the accelerated particles with a target. Depending on the application, the target might be static or a beam of particles approaching from the opposite direction. Elementary particle physicists primarily use machines with beams of electrons and positrons, or protons and anti-protons. Nuclear physicists and cosmologists often use beams of bare atomic nuclei from lead or other heavy atoms that have been stripped of electrons. These heavy ions are better suited to investigating the structure, interactions, and properties of the nuclei themselves. They can also reveal the properties of condensed matter at extremely high temperatures and densities, such as might have occurred in the first moments of early Universe.

The largest linear accelerator (LINAC) built thus far was at the Stanford Linear Accelerator Center (SLAC) National Accelerator Laboratory in Menlo Park, CA. The LINAC, shown in Figure B.14.1, operated from 1966 until 2012. Its main accelerator was 2 miles long, and it accelerated electrons and positrons. These were made to collide in a storage ring built near the end of the LINAC. SLAC’s experiments were critical in illuminating the physics of the electroweak interaction as well as probing the structure of quarks inside nucleons.

Figure 16.0.1: An aerial view of the SLAC linear accelerator. The accelerator passes under Interstate 280, which can be seen in the middle distance. Credit: SLAC National Accelerator Laboratory

Linear accelerators are well-suited to collide low mass particles such as electrons and positrons. Ring-shaped colliders, such as the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab on Long Island, New York, the Tevatron at Fermilab Fermilab near Chicago, and the Large Hadron Collider (LHC) at CERN near Geneva, Switzerland, all shown in Figure B.16.2, can accelerate particles for many circuits of the ring, making them better suited to accelerating heavier particles. Heavier particles require many circuits of the ring to accelerate to near light speed. Very high energies are achieved in the process.

The continuous deflection in circular accelerators causes the particles to lose energy by emitting photons. The radiation emitted is called synchrotron radiation and takes its name from the accelerator type. Radiation losses can be decreased by making the circular rings larger but cannot be completely avoided. Thus there is an upper energy limit on the particle energies that can be produced in accelerators.

Figure 16.0.1: AERIAL VIEWS OF RHIC, FERMILAB, AND LHC. (Top) In the Relativistic Heavy Ion Collider (RHIC), collisions between heavy atomic nuclei are used to study fundamental particle interactions and conditions in the early Universe. (Middle) The Tevatron, at the time of its construction in the late 1970s, was the largest particle accelerator in the world. It collided beams of protons and anti-protons to achieve energies of 1 TeV (10^{12} eV), hence its name. It was shut down on September 30, 2011. (Bottom) The Large Hadron Collider (LHC) accelerates protons and heavy atomic nuclei in a circular synchrotron, achieving energies of 7 TeV. It is currently the most powerful accelerator in the world. Credit: Brookhaven National Lab, Wikimedia Commons, CERN/Maximilien Brice.

The highest energy machines are usually complicated. They employ linear accelerators to inject particles into circular synchrotrons, and storage rings are used to maintain particles at their high energies. The machines are typically buried underground to provide shielding against the particles generated by the collisions. Huge and complex arrays of detectors are arranged around the points where the collisions occur. These are able to both track the resulting particles and to absorb them to measure their energy.

Large machines like the ones pictured can accelerate particles to energies that were typical in the Universe in its first fraction of a second; the current generation of machines are probing back to about the first hundred trillionth of a second (10^{-14} seconds).
