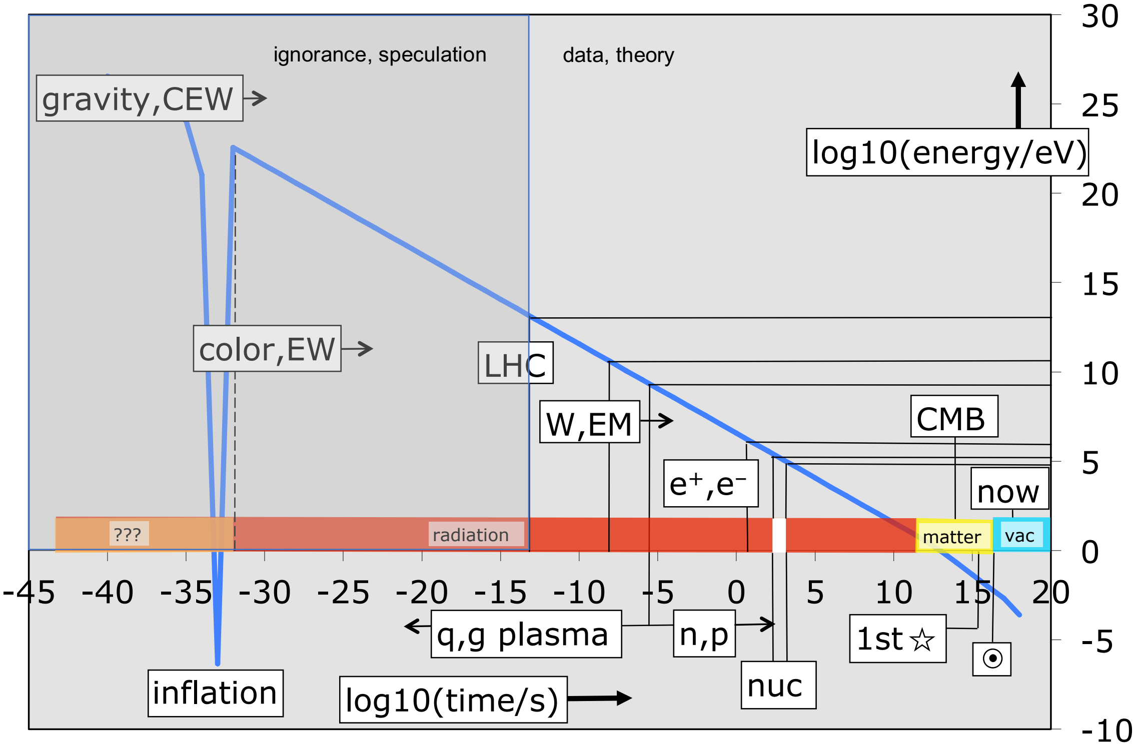
Background, 1

This course deals with the structure of matter at its extreme length scales: cosmological on the large end (on the order of 10^{26} m), sub-nuclear on the small (less than 10^{-19} m). It also deals with the now firmly established realization that the organization of matter on these two phenomenally different scales is actually intimately connected. This course is about science in its most alive and vibrant state: what we think we know about the big and small of the universe changes virtually daily. Satellite observatories and ground-based particle accelerators make what was formerly “common knowledge” obsolete at a rapid pace. That’s one reason the course is so cool.



To get a sense of what we will study, it is useful to begin with “a brief history of time” (to borrow the title of Steven Hawking’s famous best-seller: Bantam, 1998, ISBN 978-0553380163). The figure below depicts some important moments in the putative history of the universe. The axes of the graph are $\log_{10}$(time/s) and $\log_{10}$(energy/eV). Thus, a change of one unit on either axis corresponds to a change of a factor of ten in the corresponding quantity as it is usually measured. Logarithms are used because of the enormous ranges we will be discussing.

Some of what is shown is well established, but much is still highly conjectural. The conjectural parts lie behind the gray shroud labeled "ignorance, speculation." The better established are out in the light and labeled as "data, theory." The dividing line between the two is currently defined by the results of experiments conducted at the Large Hadron Collider (the LHC–crossing the border between Switzerland and France), the largest machine built so far by humans. Here are some notes about the graph.

1. One well established aspect of the current universe (i.e., the point *now* in the figure), is that we are bathed in a sea of photons, coming to us from all directions almost exactly identically, and with a frequency spectrum that is described to high accuracy and precision by *blackbody radiation.* A blackbody spectrum is characterized by a single parameter: temperature. The temperature of this cosmic microwave background (CMB) radiation is 2.725±0.001 K (an uncertainty of only about one part in 3000). The average energy of a photon in the CMB is only about 6×10^{-4} eV, which is far too small to excite a neutral atom electronic state. Thus, the CMB cannot be explained by any photon-atom interaction at the present time. Such interactions would require the average photon energy of the CMB to be about 1000 times greater than at present.
2. Blackbody radiation cools as time goes on in an expanding universe. In fact, there are several excellent observation-based reasons for inferring that the universe is indeed expanding, and has been for many years.
3. The thick blue curve in the figure above is the average photon energy in a blackbody radiation field that is cooling because of expansion and whose current temperature is 2.725 K. The rate of expansion (and hence cooling) is calculated by inserting observed values of various forms of mass and energy into a rigorously validated **cosmological model** based on *general relativity*.
4. Importantly, at an earlier time the CMB must have been hotter than it is today. The cosmological model mentioned above predicts that about 14 billion years ago the CMB would have been hot enough to interact with neutral atoms. Slightly earlier still, hot photons would have ionized all of the atoms in the universe. The crossover from ionized to neutral atoms is denoted *CMB* on the graph.
5. Though now the energy density in photons is negligible compared with that of matter, earlier than the *CMB* point photon energy dominated matter energy. Extrapolating from observed cosmic values of atomic matter, radiation, and other forms of energy, the cosmological model implies that about 13.8×10^{9} years (= 4.3×10^{17} s) ago, the universe was *much* denser and *much* hotter than at present—so dense and hot that *atoms could not have existed, nor nuclei, nor even the protons and neutrons* from which nuclei are made.
6. This state of matter and energy can be approximated in the fireballs produced at the *LHC* when protons travelling at 0.999999991 of the speed of light collide head-on. Thus, the LHC is a kind of "time machine," allowing us to probe the state of matter much earlier than today. At the energy of the LHC, matter probably consists of a small number of *elementary particles* (particles that don't appear to be made of anything smaller); six kinds of leptons (including the electron and the electron neutrino), six kinds of quarks (from which the proton and neutron are made), plus a small number of "exchange particles" (such as the photon) that are responsible for conveying the fundamental forces from particle-to-particle. This is the earliest time in the history of the universe for which we have *direct* observational evidence.

There are many well-established phenomena that appear on the history graph between the *LHC* and *now* that we will discuss in this course: the quark-gluon plasma, formation of the earliest nuclear species, the properties of the CMB, appearance of the earliest stars and galaxies, and the existence of "dark matter" and "dark energy."

Other "physics sounding stories" you might have heard about—for example, the "Big Bang," the "Big Bounce," inflation, unification of the forces, supersymmetry, extra dimensions, and elementary strings—that are proposed to have occurred at earlier times than the LHC can probe, should at this moment at least, be taken with a *large* grain of salt. These stories are mostly speculations, lacking direct empirical support.

About the times displayed on the graph: In 1899, Max Planck showed that the combination $\sqrt{\frac{G\hbar}{c^5}}$, where G = universal gravitational constant, $\hbar$ = Planck's constant/2π, and c = speed of light, had dimensions of time. This combination, now known as the "Planck time," involves gravity, relativity, and quantum mechanics, and is widely held to be the time scale at which quantum gravitational effects become important. The numerical value of the Planck time is $5.38\text{x}10^{-44}$ s, or about –43 in $\log_{10}$ units (i.e., –43 on the time axis on the history graph). All of the times noted on the history graph are relative to the Planck time.

This very quick introduction requires much more discussion, which is what this course is about. The point to remember for now, however, is that the present condition of the cosmos is intimately related to the past, and that was dominated by the physics of elementary particles. Cool, no?