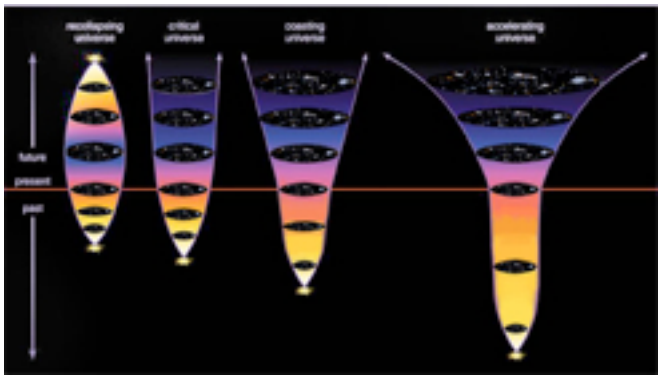
"The eternal silence of these infinite spaces terrifies me"*

Lecture 9 - December 10th, 2011

What will happen to our Universe in the billions of years in the future? We obviously can't know for sure, but we can use what we have learned from the Universe's first 14 billion years to make some guesses. Today's lecture will cover these guesses, from the mundane to the exotic.

Some of the standard possibilities are:

- **Eternal expansion and heat death**: "Not with a bang but a whimper." This is probably the most likely conclusion of our Universe's physical life: expansion outward, slowly cooling down, with everything that can decay or become cold eventually reaching its coldest, most basic state. However, if the dark energy is a cosmological constant, there is a minimum temperature the Universe can reach (remember, a cosmological constant is Einstein's idea that the vacuum of space itself might carry energy, and that energy would cause a repulsive gravitational force. This is also a good candidate to explain today's accelerating expansion of space), because de Sitter Universes, as it turns out, have a minimum temperature! This temperature is, however, very small indeed.



The standard set of possible endpoints for the Universe: collapse or eternal expansion.

- **The Big Rip:** This exotic fate is worse than heat death, if you can imagine. It's the idea that if the dark energy is something more violent than a cosmological constant, then the dark energy could eventually overwhelm all other forces in the Universe and rip everything apart -- galaxies, planets, and even atoms!
- **Big Crunch:** The idea that the Universe will end by ceasing to expand and eventually collapsing back on itself. Lots of people find this idea compelling, but it is not at all favored by current observations.

Sorting out which of these is most likely can be done using observations. This is one of the chief goals of upcoming astronomical projects like the Dark Energy Survey, which is being run by Fermilab and the University of Chicago. However, theorists have also come up with some crazy, more exotic ways that the world might end:

- **Vacuum decay:** This is the idea that the underlying vacuum of our spacetime could suddenly, spontaneously decay at a point, with the new vacuum rapidly destroying the old one. Studying this inspired the late Sidney Coleman, a physics professor at Harvard, to write what I consider to be the best paragraph ever to appear in a research paper:

*Blaise Pascal

"Vacuum decay is the ultimate ecological catastrophe; in the new vacuum there are new constants of nature; after vacuum decay, not only is life as we know it impossible, so is chemistry as we know it. However, one could always draw stoic comfort from the possibility that perhaps in the course of time the new vacuum would sustain, if not life as we know it, at least some structures capable of knowing joy. This possibility has now been eliminated."

- **Non-local regulators of eternal inflation:** This one is really far out. There are some who have proposed that the way to resolve the problems with eternal inflation (i.e., that it makes an infinite number of infinitely sized Universes and hence is impossible to use to calculate anything finite) is to posit that Universes have a maximum size after which they simply cease to exist. If true, our Universe would simply come to an end when it hits the size limit!
- **Thermal recurrence:** If the Universe ends by going to the minimum temperature de Sitter space, then what happens is that the Universe becomes an equilibrium space with a temperature. This is a space where entropy is at a maximum. One thing that people wonder about is that if entropy stops increasing by reaching a maximum, then it's hard to tell which way time is going. After all, the way we can tell which way is the forward direction in time usually is by observing the direction of entropy increase. So a maximum entropy state is, in a certain sense, timeless. A timeless equilibrium has another odd property: every once in a very long time, it can spontaneously fluctuate and make a lower entropy state! This is because thermal fluctuations are random, and random processes can occasionally make something that looks non-random, like the fabled monkeys writing out Hamlet. This leads these people to argue that another whole Universe could occasionally fluctuate into existence through these thermal effects. Obviously this wouldn't happen very often, but then again -- for a timeless Universe, what's the rush?
- **Conformal recurrence:** This is Roger Penrose's idea that once there is no longer any stuff at all in the Universe, then it ceases to have any measuring rods or clocks -- and is, in that sense, back where it started. So, he goes on to argue, a new Universe could then get going. This is not entirely unlike the thermal recurrence idea.