Energy, Matter, and Antimatter in the Universe

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It all starts with $E=mc^2$.

Remember that the early universe was very hot (energetic) and dense.

With lots of energy, lots of particles (matter and radiation) can be created. When there are many particles per volume (dense), the particles can interact and return to being energy (annihilate).

This makes all matter, radiation, and energy in thermal equilibrium - a very simple initial state, characterized by its energy or temperature, $E=kT$. 
Before the Beginning?

We don’t know the physics to describe the extra extra early universe, when the age is of order the Planck time $t_{Pl} = \sqrt{G \hbar/c^5}$ ($\sim 10^{-43}$ s).

But it doesn’t matter. These initial conditions were wiped out by a combination of the thermal equilibrium (many interactions of energy ↔ matter) and an episode of *Cosmic Amnesia* known as inflation.

*Inflation vastly expanded* each small volume of the universe (which had achieved thermal equilibrium) into a huge volume, such that any observer could only see conditions within the previously small patch (*visible universe << full universe*).
The only event as important as inflation is the end of inflation.

First, inflation makes the rest of the full universe out of contact. Then, at the end of inflation, all the energy from the *inflaton*, the quantum field driving inflation, gets converted into matter and radiation (reheating).

This one-two punch removes any “memory” of the earlier stages of the universe, hence cosmic amnesia.
We know very little about inflation.

We don’t know the nature of the inflaton, what makes inflation stop, or when. It could have happened anytime between $10^{-37}$ s and $10^{-12}$ s ($10^{25}$ and $10^{12}$ eV).

But it does solve many puzzles (smoothness) and predicts the origin of perturbations in matter and radiation from quantum fluctuations, with special random (scale invariant) properties. Detected $\checkmark$!

Inflation also predicts fluctuations in spacetime itself (gravitational waves), which experiments are gearing up to search for.
Topological Defects

Inflation is an example of a phase transition, where a symmetry of nature is broken.

Abdus Salam, 1979 Nobel Physics laureate, gave the example of napkins at a dinner party.

Phase transitions can leave behind discontinuities called topological defects. These can be 0-D (pointlike) - *magnetic monopoles*, 1-D (linelike) - *cosmic strings*, 2-D (sheetlike) - *domain walls*.

We have never detected any on cosmic scales, but they would point us toward deep physics.
After inflation, reheating repopulates the universe with particles. (Cosmologists often call any form of mass-energy with much more energy than mass by the name radiation, and this is meant to include photons, neutrinos, and relativistic matter.)

Because the universe is still hot and dense, many interactions occur and thermal equilibrium holds.

What determines the interactions and what happens when equilibrium breaks down?
Particle Interactions

For one thing, remember $E=mc^2$. Particles cannot be created if there is not enough energy, so as the universe cools, very massive particles cease being created. They may decay into lighter particles or may stick around.

Particles can also be created from interactions of other particles. To do this, the particles have to run into each other.

Although we call the universe dense, it’s actually more dilute than water by the time it’s 10 s old. So the odds of 3 particles being in the same place at the same time are low (this is why primordial nucleosynthesis can’t create carbon or heavier elements).
Particles have pair interactions, mano a mano. The probability of their running into each other depends on their cross section.
Cross section $\sigma$ does not depend only on the geometric size of the particle, but the strength of its attraction (under one or more of the four forces).

The interaction rate also depends on the number density $n$ of particles (the more densely packed, the easier to collide), and the velocity $v$ of particles (the speedier, the more chances for encounter).

The probability of encounter in a time $t$ is the effective volume covered, $V = \sigma vt = \sigma L$, times the number density, i.e. the number of particles in the volume.
Freezeout

As the universe expands, the number density of particles become diluted. Also, the cross section often depends on energy and can get smaller.

Eventually, it is very unlikely for particles to interact within a time as long as the age of the universe, $H^{-1}$, and reactions cease. This is called freezeout because the number of particles stays constant thereafter.

Note that more weakly interacting particles freezeout sooner (smaller cross section), when the universe was denser, and so have a larger abundance today. Dark matter, contributing 20% of the energy density today, may well be made of weakly interacting massive particles (WIMPs).
When energy is converted into particles, it must conserve total energy and momentum, and also must obey certain quantum properties. E.g. a lepton can’t become a baryon.

If the energy creates a particle and its antiparticle, then quantum numbers are automatically conserved. Photons are their own antiparticle, but matter partners with antimatter, e.g. electron and positron or proton and antiproton.

When a particle and antiparticle meet, they convert back into pure energy.

\[e^- + e^+ \rightarrow 1 \text{ MeV} \quad \text{person} + \text{person} \rightarrow 1000 \text{ Mton blast}\]
So where is all the antimatter?

Or, why is there even any matter? When the universe cools from expansion it can no longer create matter or antimatter, so they should annihilate each other, leaving only energy (the CMB).

Something must break down! We detect plenty of matter (look around) but the only antimatter is that created anew in energetic processes. (Antimatter was identified in the lab in 1932, the positron.)
Dirac (Nobel 1933) predicted antimatter in 1928. He realized something was needed to balance matter in quantum theory, and treated antimatter as “holes”, what you have when you take away from nothing (the vacuum).

Sakharov (Nobel 1975) laid out three conditions needed for matter-antimatter asymmetry, such as we see:

• Breakdown of thermal equilibrium (phase transition)
• Violation of matter-antimatter symmetry (CP)
• Violation of baryon number
Where is the Antimatter?

How do we know the whole universe is matter?

Solar system - direct probes.

Larger scales - gamma rays. Annihilation radiation is very characteristic line (e.g. $e^+e^- \rightarrow 1.02 \text{ MeV}$).

Problem of separation. Large scales have not been in causal contact since inflation.

Particle scales - do see symmetry, except in special CP violating systems (K mesons, Nobel 1980; B mesons).
Following Sakharov, we guess that some symmetry breaking occurred at high energy, allowing a slight excess in baryons over antibaryons to be created, about 30,000,001 per 30,000,000.

Once the universe cooled so matter-antimatter creation ceased and they only annihilated, this left behind the sole extra baryons (1 part in $3 \times 10^7$ of what would be expected).

This is directly evident today in the photon-baryon ratio. In thermal equilibrium, there should be equipartition - equal numbers of all types of particles. But today the photon-baryon ratio is $2 \times 10^9$, not nearly 1 (extra species give $10^9$ not $10^7$).
Photons and Baryons

The high photon-baryon ratio has important consequences for the universe. Since there are so many more photons than expected per baryon, the photons have influence even when their energy is below the interaction energy (there are always a few photons more energetic than the average).

This keeps the universe ionized longer than otherwise, preventing atoms from forming til later, and preventing perturbations in the baryon density from growing (structure formation).

This moderating influence is like the ocean’s effect on the climate of land (heat capacity).
Today one of the great puzzles of physics is baryogenesis, the origin of the matter-antimatter asymmetry. We measure an asymmetry in special particle physics systems, but don’t understand where the primordial $10^{-8}$ comes from.

We also don’t know if neutrinos are their own antiparticle. Experiments may reveal this in the next few years!

So we don’t understand dark energy, don’t understand dark matter, and don’t even understand baryons! Exciting mysteries everywhere we look.