Age, Evolution, and Size of the Cosmos

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Let There Be a Big Bang!

- Let’s start at the start (13.82 billion years ago). But how do we know the age of the universe to such high precision today?

- Various independent methods
  - Differing models of cosmic evolution make unique predictions for the pattern of the Cosmic Microwave Background Radiation. Amount of photon redshift can vary
  - Cepheid variable stars, Type Ia supernova explosions, etc. allow us to robustly estimate the value of Hubble’s constant. We can then reverse the expansion of the universe on paper with mathematics
  - Density over time: infinite at beginning
  - We can find the oldest stars and use knowledge of stellar evolution (for example, white dwarf cooling) to get a lower bound within 0(billion) years of the beginning (also, globular star clusters)

- All agree within the uncertainties, wow!!!
• Popular science book *Wrinkles in Time* by George Smoot was a significant influence upon the form and style of today’s slides.
Origins

• The great unknown
• A black hole, a singularity? Naked (no event horizon)?
• Zero-energy quantum fluctuation?
• A pre-geometry of foam-like space-time whose laws of physics are not yet known
• Need new physics to describe and explain

Time
Temperature
Energy

0 seconds
Infinity*
Infinity**

Black Holes and Time Warps by Kip Thorne

* Unit of temperature will be Kelvin. Room temperature is ~300 K. Absolute zero (0 K: lowest possible, no motion) is -273 °C, -459 °F

**The unit of energy will be electron-Volts (eV). 1 eV is the amount of kinetic energy gained by an electron experiencing an electrical potential of exactly 1 Volt (V). Couched in a familiar term, 1 Calorie = 4,184 Joules (J) = 2.611 x 10²² eV
End of Quantum Gravity Epoch

- The strong nuclear, weak nuclear, and electromagnetic forces are unified into one indistinguishable force.
- This period is often referred to as the Grand Unification (Theory) or GUT Epoch. Ends after “Planck time” (~5 x 10^{-44} s)
- During this epoch, there likely was a very rapid, accelerating expansion of the universe (the cosmic inflation). This inflation made our universe very large and flat, but also produced ripples in the spacetime it was creating.

10^{-43} seconds
10^{32} Kelvin
10^{28} eV (Planck energy scale)
End of GUT/Inflationary Epoch

- The strong force becomes distinct from the weak and electromagnetic forces: end of grand unification of forces.
- The universe is a plasma of quarks, gluons, electrons, photons, neutrinos, and other particles.
- Inflation ends and the expanding universe coasts, gradually slowing its expansion under the pull of gravity.
- At $10^{-13}$ s / $10^{17}$ K / $10^{13}$ eV energy per particle of the LHC (Large Hadron Collider) accelerator at CERN in Europe
End of Electroweak/Quark Epoch

- Electromagnetic & weak forces separate $(10^{-12} \text{ s})$
- An excess of one part in a billion (a thousand million) of matter over antimatter has developed.
- Quarks are able to merge to form protons and neutrons: no longer in quark-gluon plasma $(10^{-5} \text{ s})$
- Positrons finished annihilating to gammas $(10^{-6} \text{ s})$
End of the Neutrino Equilibrium

• Neutrinos decouple (more precisely, 0.2 s)
• After electron-positron annihilation residual electrons and cosmic background radiation main active constituents on the universe
• Ratio of neutrons to protons is now frozen

1 second
$10^{10}$ K
$10^6$ eV
Protons and neutrons are able to bind together to form nuclei since their binding energy is now greater than the cosmic background radiation energy, so the background of light (photons) can’t break them up anymore.

A rapid synthesis of light nuclei occurs – first deuterium (heavy hydrogen: one proton and one neutron), then heavier elements, primarily helium but up to lithium (three protons and four neutrons) nuclei.

About 75% of the nuclei are hydrogen (one proton) and 25% are helium (two protons and two neutrons); only a smattering are another element. The heavier elements are later formed by nuclear burning in stars.
End of the Photon Epoch

- Matter (atoms) begins to dominate over radiation (equal density point) at \(~1,000\) years after the Big Bang.
- Matter and the cosmic background radiation decouple as electrons bind with nuclei to make neutral atoms.
- The universe becomes transparent to the cosmic background radiation, making it possible for COBE, WMAP, and Planck spacecraft to map this epoch of last scattering (also given the name of recombination).

380,000 years
3,000 K / °Celsius
0.25 eV
End of the Starless Epoch

- Clusters of matter have formed from the primordial ripples to form the first stars, re-ionizing the universe and bringing back the nuclear fusion processes; soon very first galactic nuclei, quasars.
- In the interior of stars, the burning of the primordial hydrogen and helium nuclei synthesizes the heavier nuclei such as carbon, nitrogen, oxygen, and iron. Clouds of hydrogen collapse due to gravity.
- Elements are dispersed by stellar winds and supernova explosions, making new stars, planets, and life possible. We are of star material.
- At ~2-billion-year mark first proto-galaxies, galaxies, supernovae
Up to the contemporary era

- 5 billion: galaxy clusters, superclusters take shape. Heavy atoms
- 9.1 billion: Our solar system condensed from the remnants of earlier stars. Chemical processes have linked atoms together to form molecules like DNA, then complicated solids and liquids.
- ~10 billion: first life-forms (on Earth) about 4 billion years ago wow
- NOW: Humankind has emerged from the dust of the stars to contemplate the universe surrounding it -- thinking, pondering...

13.8 billion years
2.725 K / -270 °C
2e-4 eV
The Size of Our Universe

• The visible part of the universe is 93 billion light-years in diameter (sphere defined by how far light has been able to travel since the beginning)
  – We can determine this by age and expansion rate and speed of light. The naïve answer of 13.8 light-years wrong because space expands faster than the speed of light
  – This does not imply universe is finite and spherical

• Entire universe is at least 10 trillion light-years “across” but may be infinite. Based on geometry we are right on the border between finite (opposite of going on forever – having a boundary of some kind with countably many galaxies and stars) and infinite
  – Occam’s razor: same outside visible part as inside. Same laws

• We cannot now (at least not as of yet!) have a definitive answer on the size of the total universe, while there may be others universes beyond it…