Origins & Evolution of the Universe

an introduction to cosmology – Fall 2014

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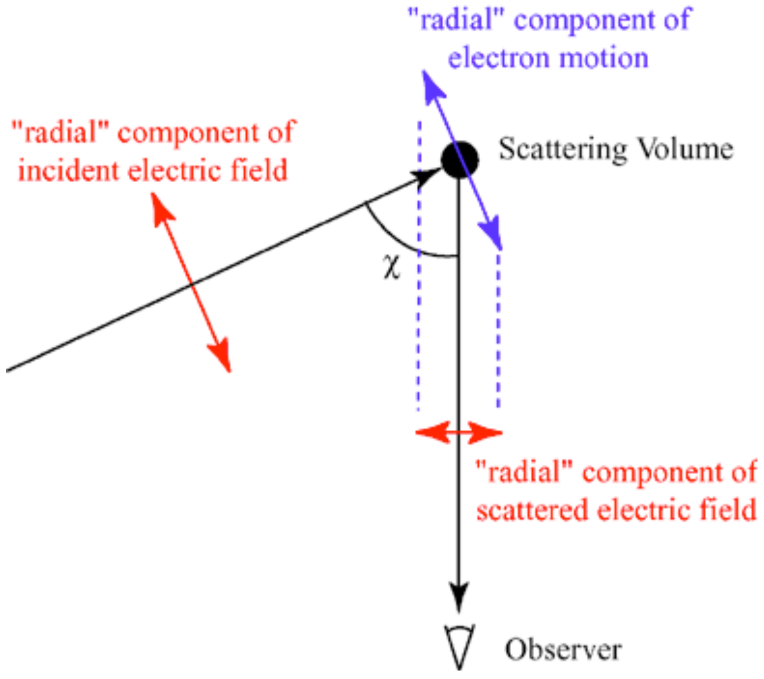
http://www.strw.leidenuniv.nl/~hoekstra/TEACHING/OEU/OEU.html

Thomson scattering

Photons and charged particles in a plasma interact. The dominant process is the elastic scattering of radiation by a charged particle. At low energies this is called Thomson scattering.



The cross section is independent of wavelength and largest for electrons.

Evolution of temperature

Currently the CMB and matter are decoupled: the Universe is transparent to the 2.73K radiation. Note that the most of the hydrogen is ionized again, but the density is too low now. Neutral hydrogen has a low scattering cross section.

If we consider the evolution of temperature of decoupled gas and radiation we find that:

- $T \propto (1+z)^2$ for matter and $\propto (1+z)$ for radiation. The temperature of matter rises faster than that of radiation until decoupling time t_d when matter and radiation were coupled. Before t_d the temperatures were equal by thermal interactions.
- After t_d the matter density evolves $\propto (1+z)^3$ and the radiation density as $\propto (1+z)^4$.

Before t_d they evolve as $\propto (1+z)^{4+\epsilon}$; $\epsilon(z)$ due to exchange of energy with matter. $\epsilon(z)$ is small because of the large photon-baryon ratio.

Evolution of temperature

As $\epsilon(z)\approx 0$ the temperature increases as $T \propto (1+z)$. Note that also T^3/ϱ remains constant $\Longrightarrow$ σ_{rad} remains large.

Further back in time, the matter becomes relativistic and the total equation-of-state becomes $w=1/3$: $T \propto (1+z)$

The temperature keeps rising to higher and higher temperatures.

Hot Big Bang!

Physical changes in the plasma

As the plasma gets hotter, more and more particle reactions become possible and the composition changes.

For this reason particle physicists express temperatures in eV:
$1eV=1.6x10^{-19}J=k_B(1.16x10^4K)$

When the temperature exceeded 1MeV electron-positron pairs were created and annihilated: $e^- + e^+ \rightleftarrows \gamma + \gamma$: this is called the "lepton era".

Above 130 MeV, pions are created: "hadron era"

Above 200-300 MeV hadrons fall apart into their constituent quarks: "quark soup era"

Baryon asymmetry

Why is there more matter than antimatter?

During the hadron era there must have been many proton-antiproton pairs, etc. Almost all of these annihilated as the Universe cooled, but a residual amount of matter remained.

Below $T \sim 10^{15}$ GeV (GUT scale) baryon number is conserved in the standard model of particle physics.

Above T_{GUT} the densities of matter, antimatter and photons were approximately equal and the asymmetry after the GUT era $\sim 1/\sigma_{rad}$: very small!

The singularity

The expansion in a matter or radiation dominated universe decelerates.

At t=0 we have a=0: the density is infinite

Our description of the physics breaks down: the fundamental limit is the Planck era when quantum mechanical effects and strong gravity occur on similar scales; we need a theory of quantum gravity.

Can we avoid the singularity?

Planck scale

The quantum size of a particle of mass m is the Compton length: $\ell_C = \hbar / mc$.

The relevant size for gravity is the Schwarzschild radius $\ell_s = 2Gm/c^2$.

When the two coincide we need both GR and quantum mechanics to describe the physics: the Planck scale.

In the first 10^{-43}s particles have Planck masses separated by less than a Planck length.

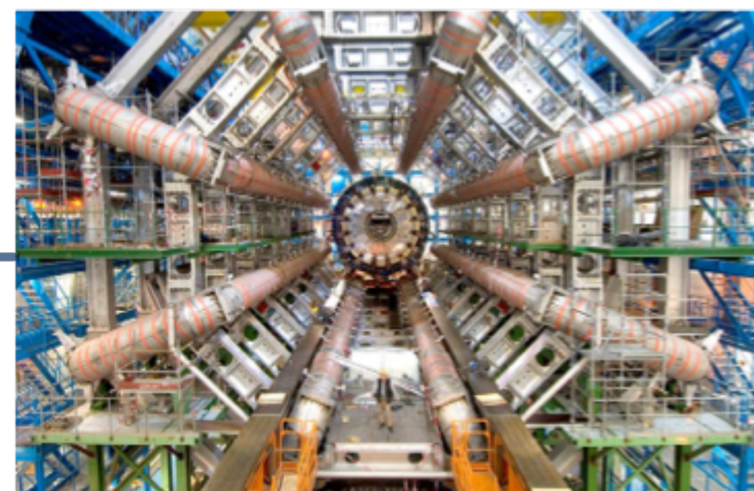
Experimental constraints

quantum gravity: ~10^9J

GUT: ~10^6J

cosmic rays: ~50J

LHC: ~10^{-6}J



nuclear reactions: ~10^{-12}J

atoms: ~10^{-18}J

ENERGY

Dark energy problem

The nature of dark energy is not understood, and the observed value is extremely small in natural (=Planck) units. This is one of the largest problems in physics.

The solution may require a better understanding of the quantum mechanical and gravitational properties of the vacuum.