Computing Our Universe

Cosmology V – History of the Universe

Eric Linder

1 SCALING

Early universe is **radiation dominated**

$w = 1/3$: photons, neutrinos, relativistic particles

In **thermal equilibrium** because timescale for interactions much shorter than timescale of expansion H^{-1}.

Characterize by single temperature T.

Rem $T \sim a^{-1}$, e.g. by Stefan-Boltzmann law, so

Early universe was hot, dense state.

Adiabatic expansion $\Rightarrow$ cools.

Cf. breath through pursed lips feels cool (expanding out from the narrow opening), but from open mouth feels hot.

$T \sim a^{-1}$ and $a \sim t^{1/2}$ (radiation domination) $\Rightarrow$ temperature-time relation $T(t)$:

$$T \approx (t/1\,s)^{-1/2}\,MeV \qquad T > T_{eq} \approx 1\,eV, \quad t < t_{eq} \approx 10^{12}\,s$$

$$T = 2.73(t/t_0)^{-2/3}\,K \qquad T < T_{eq} \approx 10^4 K, \quad t > t_{eq} \approx 50000\,y$$

$$T(z) = T_0(1+z) = 2.73(1+z)\,K = 2.4 \times 10^{-4}(1+z)\,eV$$

Useful in determining when various particle interactions take place.

Adiabatic expansion $\Rightarrow$ entropy in the radiation field (cf. 1st law of thermodynamics) is constant: $S \sim \rho V/T$ ~const. The entropy density

$s \sim \rho/T \sim T^3 \sim n_\gamma$ is not, but the **specific entropy**, the entropy density per (conserved) baryon is constant: $s/n_b \sim n_\gamma/n_b \sim$const. More commonly as **baryon-photon ratio**

$$\eta \equiv n_b/n_\gamma = 2.7 \times 10^{-8}\Omega_b h^2.$$

Since $\Omega_b h^2$ is found to be ≈ 0.01 this says there are about 10^9 photons per baryon, or the specific entropy is about 10^{10} in units of Boltzmann's constant. Such a high entropy universe is called a *hot universe* (independent of temperature) and is in marked contrast to, say, a star, which has a specific entropy of order one. This will have important implications for nuclear reactions in the early universe and the production of light elements.

2 BACK TO THE BIG BANG

As we look back in time we soon lose our observational capabilities to directly detect the physical conditions in the universe and must rely more and more on theory, plus experiment from other arenas. How confident should we be about this extraordinary extrapolation?

Particle accelerators probe energies up to 10^3 GeV, equivalent to the temperature of the universe at $z < 10^{15.5}$.

Lab experiments probe densities up to nuclear densities, 10^{14} g cm^{-3}, equivalent to $z < 10^{14.5}$.

These are well before the epoch of primordial nucleosynthesis so we can retain a fair degree of confidence in our "history of the universe".

FIGURE 4.2: History of the Universe

3 EARLY UNIVERSE

I will say little about the universe before nucleosynthesis, with the exception of inflation, because of the uncertainty and fortuitously the largely irrelevance to large scale structure formation.

3.1 Nucleosynthesis

The early universe is too hot to prevent atoms from being ionized (hence destroyed), and at early times too hot for even nuclear binding. **Light elements** (principally H, He, Li) are formed when the universe cools to ≈ 0.1 MeV ($t \approx 1$ min) but heavier elements cannot be formed due to the diffuse density: there is a block to forming carbon (and heavier) because the 3α process cannot run.

The abundance of light elements produced primordially depends cosmologically only on the expansion rate H and baryon-photon ratio $\eta \sim \Omega_b h^2$. Excellent agreement with abundance measurements is obtained for

$$\Omega_b h^2 = 0.0125 - 0.02$$

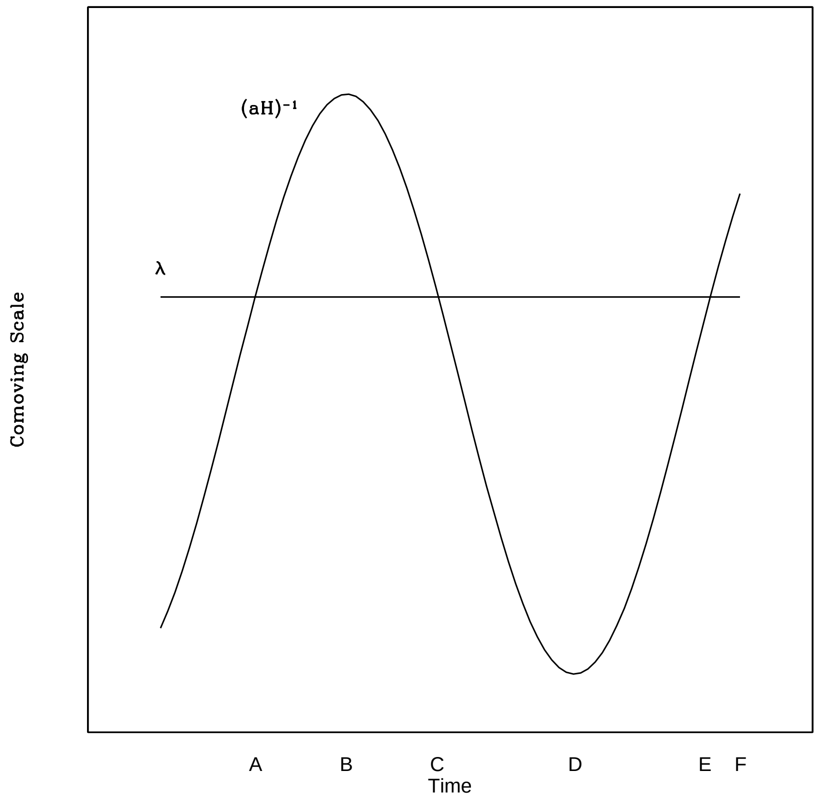
3.2 Inflation

• **flatness problem** – why is the density close to the unstable point $\Omega = 1$?

• **horizon problem** – why are parts of the sky that should not have come into causal contact the same temperature?

• **structure problem** – why are there density fluctuations on such large scales, that were acausal?

• **particle physics** issues.



To satisfy causality, the scales of interest must at some previous time have been within particle horizon. To appear acausal today (or in the recent past) they must have grown more quickly than the horizon. The figure shows this in comoving coordinates, where the comoving scales are constant in time and the comoving horizon $\sim (aH)^{-1}$.

The condition that $(aH)^{-1}$ decreases in time is precisely $\ddot{a} > 0$. This accelerated expansion is called **inflation**. From the acceleration Friedmann equation we see this only happens if at some epoch the universe was dominated by exotic matter with $p < -(1/3)\rho$, i.e. $w < -1/3$.

Usual models of inflation have four implications:

- $\Omega = 1$ (flat universe)
- gaussian distribution of density perturbations

• $n = 1$ (scale invariant potential perturbations)

• more accurately, gravitational waves plus tilt

because the radius of curvature is blown up to very large scales, so the universe appears flat: $\Omega = 1$;

Density perturbations are seeded at the end of inflation by quantum processes, implying the spectrum of perturbations is **gaussian** (random phase) and **scale invariant** in the gravitational potential: $\delta\Phi \sim \lambda^{(1-n)/2} \sim$const, so $n = 1$.

A more realistic calculation implies the production of **gravitational waves** as well, and a slight spectral **tilt** $n - 1 \ll 1$.

3.3 Matter-Radiation Equality

At $z_{eq} = 23900\,\Omega_0 h^2$ the universe changes from radiation domination to matter domination. This has two important implications for large scale structure:

• the transition from $a \sim t^{1/2}$ to $a \sim t^{2/3}$ creates a feature in the power spectrum of density perturbations on the horizon scale at this epoch, k_{eq}

• matter that does not couple to photons – like some **dark matter** – can start to cluster gravitationally

4 COSMIC MICROWAVE BACKGROUND RADIATION

Here I only address the thermal history; see Special VII for more. Photons couple (stay in thermal equilibrium) with matter through:

• e^+e^- creation/annihilation until $z \approx 10^8$, then

• free-free/bremsstrahlung until $z \approx 10^6$, then **thermalization epoch** over and any energy inputs at $z < 10^6$ disequilibrate photons – distort from **blackbody** – by

- Bose-Einstein distortion $\sim$ chemical potential $\mu = 1.4\,(\Delta E/E)$ at $z \approx 10^4 - 10^6$,
- Compton distortion: $y = (\Delta E/E)/4$ at $z < 10^4$

Observed limits $y < 1.5 \times 10^{-5}$, $\mu < 9 \times 10^{-5}$ $\Rightarrow$ Quiet Universe.

Photons start uncoupling from matter as ionization weakens, allowing

- **recombination epoch** $z_{rec} = 1300$ as electrons + nuclei $\rightarrow$ neutral atoms, which weakens electron scattering $e\gamma \rightarrow e\gamma$ causing
- **decoupling epoch** $z_{dec} = 1100$, then
- **last scattering surface** $z_{lss} = 1050$ when photons **free stream**, carrying preserved imprint of matter density perturbations at z_{dec}

Those primordial density perturbations, now free from radiation damping grow thru **gravitational instability**

- initially linearly, $\delta\rho/\rho \sim a$, then
- enter **nonlinear regime** of growth as $\delta\rho/\rho \geq 1$, at $z \approx 1 - 5$ depending on scale (mass), and
- form galaxies, clusters, voids, stars, us!