§ 3 – Observational Cosmology – Evolution from the Big Bang

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Topic	Sources	Comments
Particle horizon: Concept - the observable Universe	RR(4.10)	*The particle horizon is often referred to simply as "the horizon".*
Horizon and flatness problems: Problems of the Big Bang model: Flatness - why is Omega close to 1 ? Horizon - unconnected regions have same CMB temperature	L(12.1), RR(p.161-2) L2(13.1)	
Inflation: Early rapid exponential expansion Solves horizon & flatness problems May be due to a phase of high vacuum energy density	L(12.2-12.5), RR(5.4), NW(Part 4) L2(13.2-13.5)	See sections I-III of the Guth paper for more detail
Evolution of density and temperature: Effect of expansion on density and temperature Differing behaviour of matter & radiation - matter and radiation dominated eras	RR(5.1 & 5.2) , L(9.1, 10) L2(10.1,11)	*See especially RR Figs. 5.2 & 5.3*
Cosmic nucleosynthesis: Key reactions Origin of the helium fraction Why are only light elements synthesised?	RR(5.3), L(11) L2(12)	*Add to your notes from Unit 1 - this time tracing the key reaction stages.*
Recombination (decoupling): What is this, when and why did it happen?	RR(5.2), L(9.3) , L2(10.3-10.4)	
Growth of structure From CMB fluctuations to today's galaxies Growth of density perturbations Collapse and virialisation Hierarchical merging Jeans mass and the effects of pressure on baryons	RR(5.5,6.1-6.2), L(13), L2(A5.2, A5.4), B(3.1, 4.1, 5.1-5.3), Unit 3 lecture	*Major section - see detailed guidance here.*
Galaxy formation Cooling of baryons Monolithic collapse and hierarchical models	Unit 3 lecture, RR(2.5) Detailed treatments in papers by Ellis (observational), and Baugh and Cole (theoretical modelling).	*R-R gives only a little on this important topic, and Liddle almost nothing. The papers referred to here are more detailed than you need, but you could usefully skim through some of them.*
Cosmological simulations Growth of large-scale structure depends on cosmological parameters	Hubble volume , VIRGO, Local volume	*Note that some simulations include only dark matter.*

Evolution of the Universe

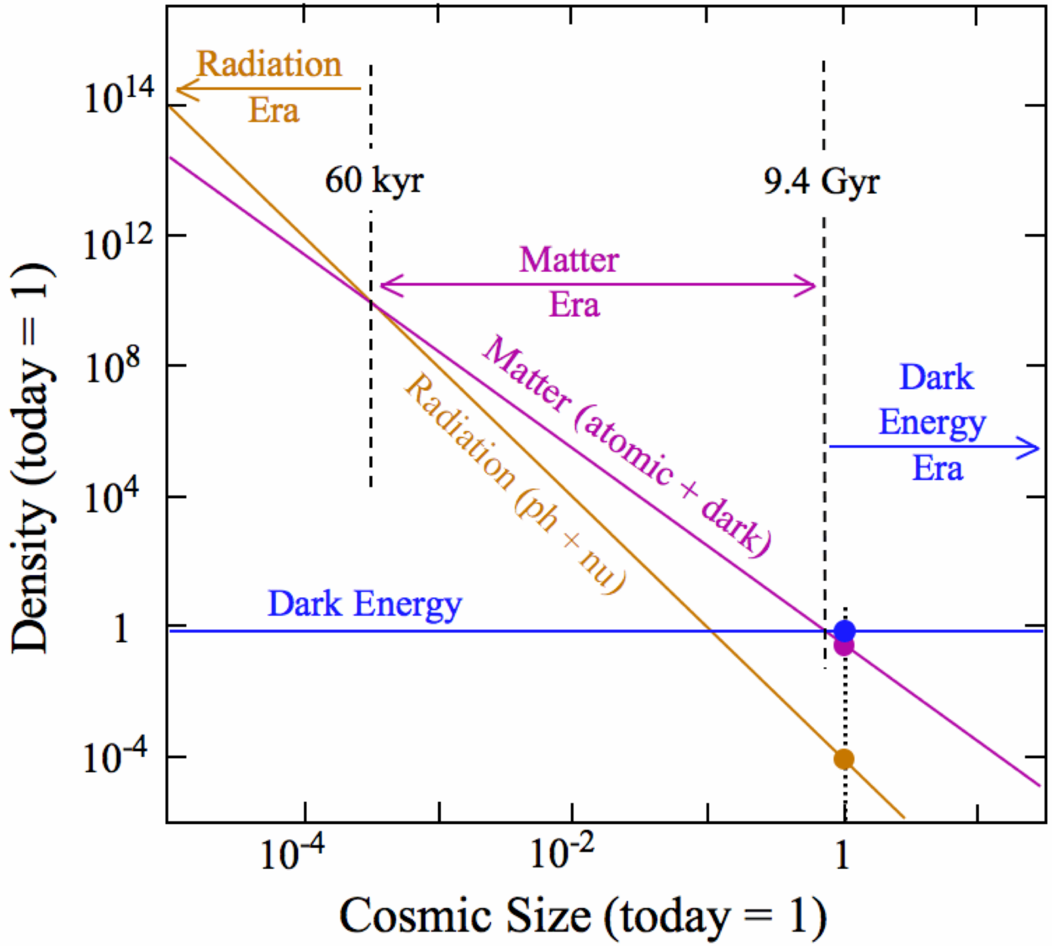
Energy density

The Universe is made of three components;

- Matter: both dark and baryons
- Radiation
- Dark energy (vacuum energy)

The energy density of each component evolves differently with a (as a^{-3}, a^{-4} and a^{0} respectively).

a is the scale factor of the universe. It is equal to 1 today, and was smaller in the past.



Recombination and the CMB

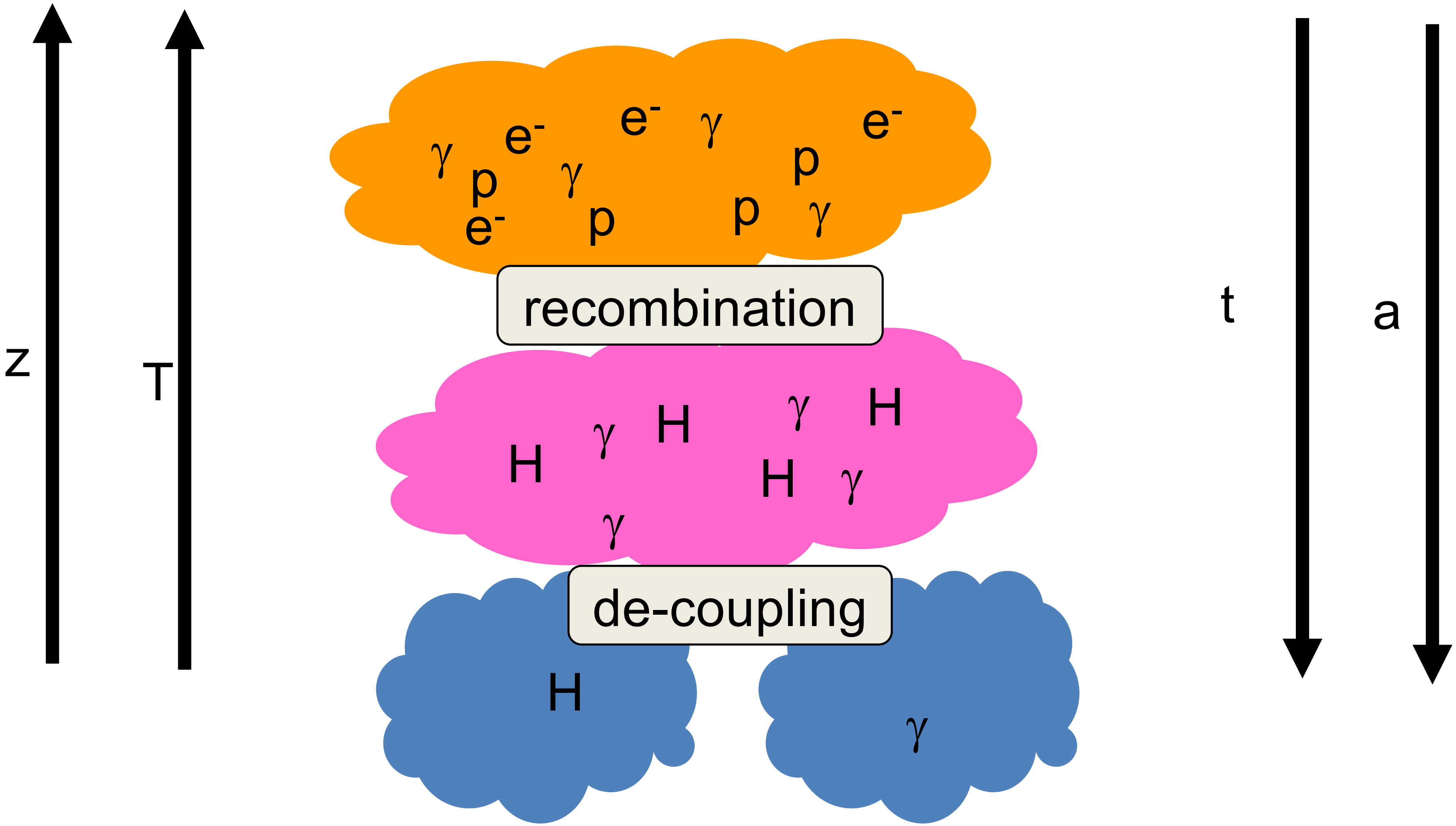
The early universe was ionized. And the high scattering cross-section of photons off free elections (σ_T=6.65 × 10^{-29}m^2) means they are tightly coupled.

As the Universe expands and cools, the radiation energy density drops as a^{-4}, whilst the energy density of matter drops only as a^{-3}. **Equality of the density of matter and radiation** is reached at T~9700 K (at t~50,000 yr), **recombination** follows at t~240,000 yr when T~3700 K. Thus, the baryons become neutral.

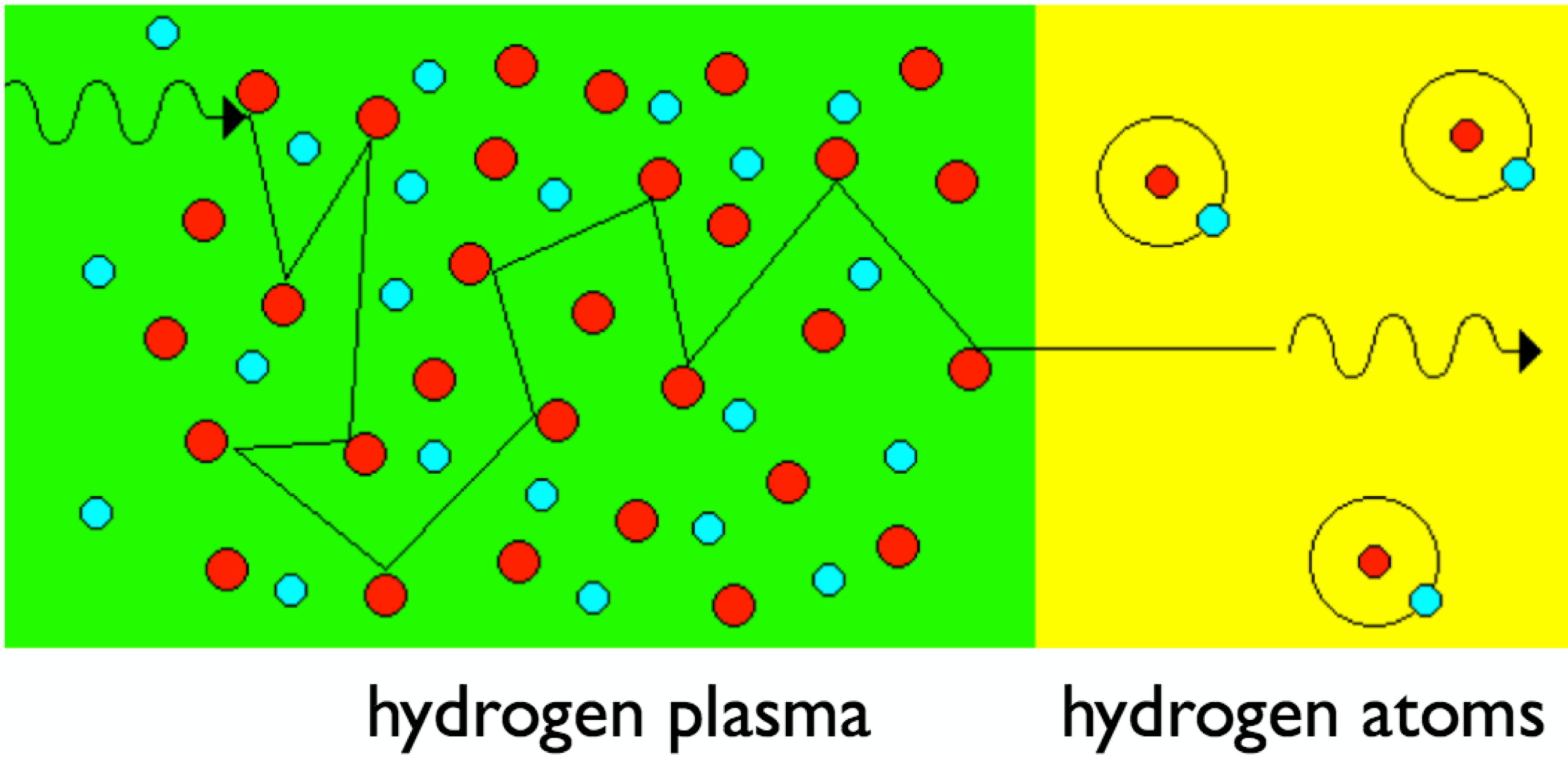
The scattering cross-section of photons off bound elections (away from line transitions) is much lower. So, following some further expansion (t~350,000 yr (z=1100) at T~3000 K) , the cross section has dropped enough for radiation to **decouple** from matter.

The CMB photons effectively travel freely from this **last-scattering surface**, with their blackbody spectrum cooling from 3000 K to 2.7 K as the universe expands by a factor of 1100.

De-coupling and Recombination



Surface of last scattering

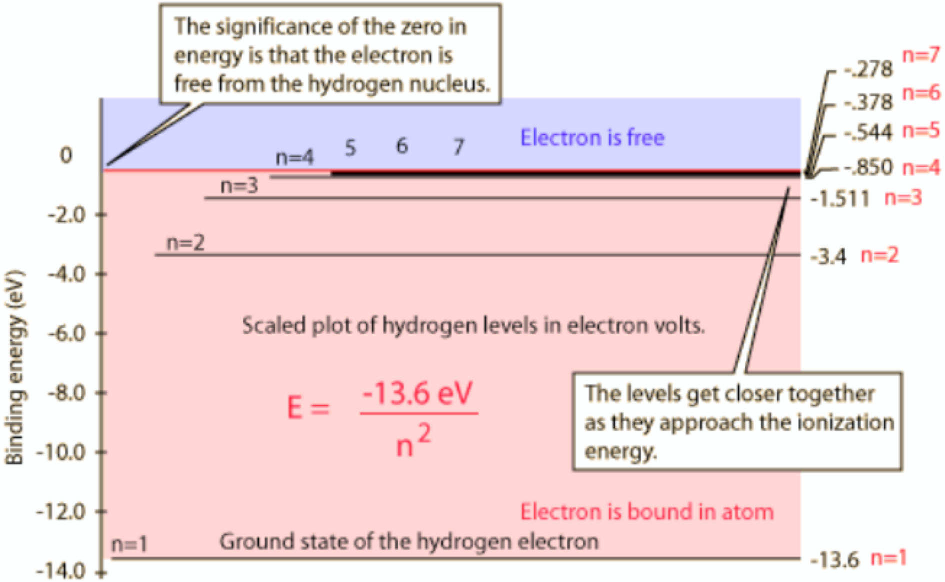


Decoupling of photons

- Mean energy of photons

$$\langle E \rangle = 3k_B T$$

- Ionizing temperature of hydrogen: 13.6 eV
- However, $n_\gamma/n_b \sim 10^9$
- Decoupling at T ~ 3000 K ~ 0.2 eV



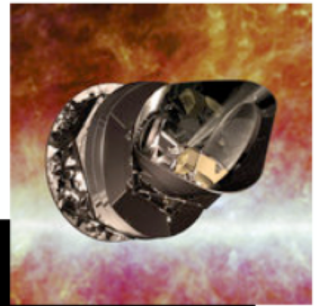
$$T = \frac{\langle E \rangle}{3k_B} = 5.4 \times 10^4 K$$

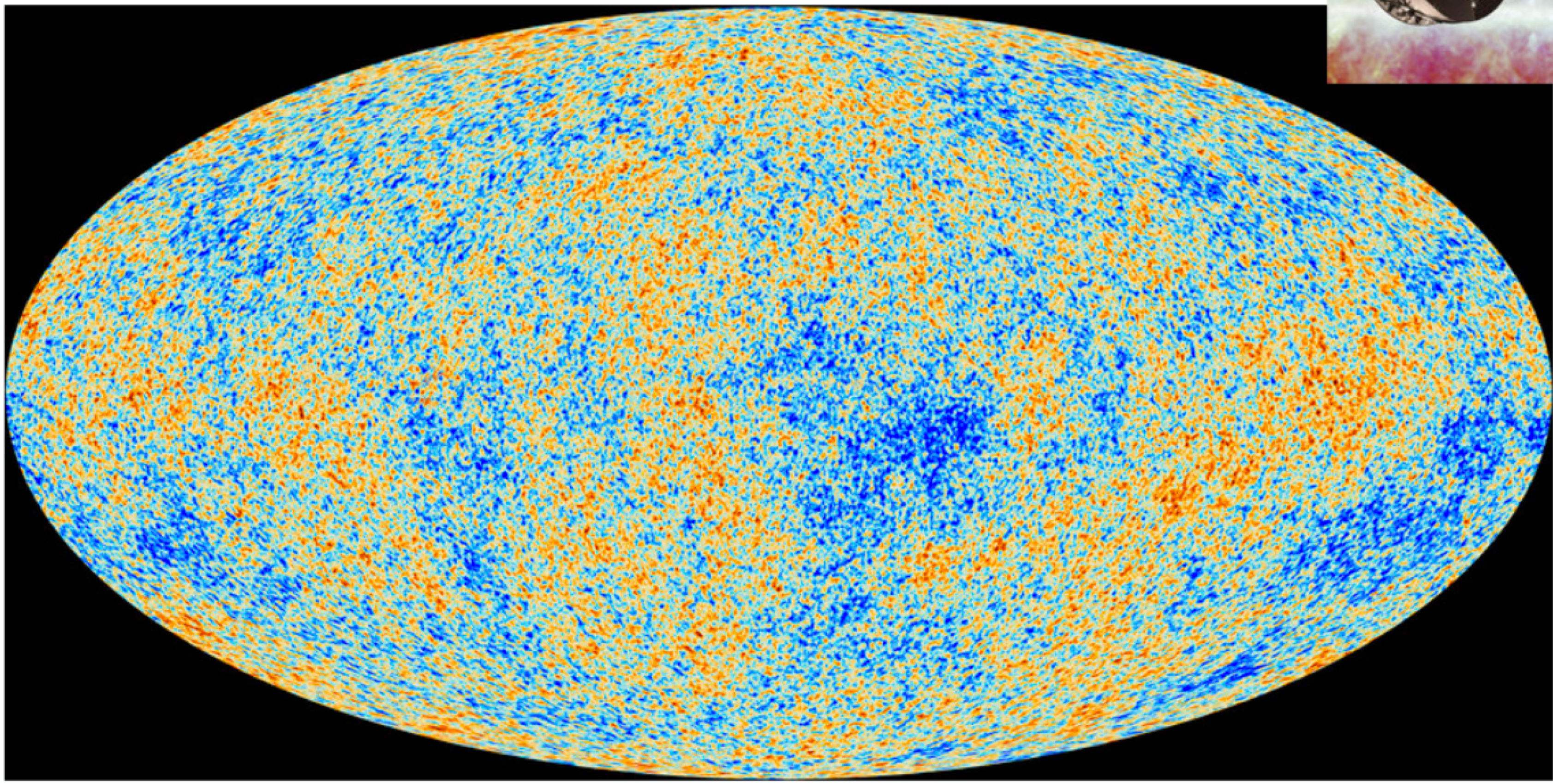
$$(1+z) = \frac{T}{T_0} = \frac{3000}{2.7} = 1100$$

$$1/k_B = 1.16 \times 10^4 K/eV$$

Planck

CMB





Flatness problem

The early universe is radiation dominated.

$$|1 - \Omega|_r \propto a^2 \propto t$$

In the early universe, the relevant timescale is the Planck time.

1/Mp = 5.4 X 10^-44 seconds

A closed universe will reach maximum size on this timescale.

An open universe will quickly have density much less than critical.

In the early universe rho = rho_crit to within 10^55 for the universe to last 10^10 years.

Horizon problem

For a flat radiation-dominated universe *a(t)* scales as $t^{1/2}$. Hence $H=1/2t$ and $d_{\mathrm{hor}}(t)=2ct=c/H$.   (N.B. $d_H=c/H$ is known as the Hubble distance.)

Naively, the horizon distance at decoupling would therefore be approximately $2ct$, which for decoupling at time t=0.35 Myr and z=1100 (see below) gives $d_{\mathrm{hor}}\approx$0.2 Mpc. Such small regions would subtend an angle on our sky of only ~1° , which means that the remarkable uniformity of the CMB across the whole sky is unexplained.

How can we fix the Horizon and Flatness problems?

Inflation and the horizon

The idea of inflation was motivated primarily by the flatness and horizon problems.

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Inflationary universe: A possible solution to the horizon and flatness problems

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The standard model of hot big-bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separated regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

The idea c … rizon problems.

ΣV (5)
Dec 7, 1979

SPECTACULAR REALIZATION:

This kind of supercooling can explain why the universe today is so incredibly flat — and therefore ~~why~~ resolve the fine-tuning paradox pointed out by Bob Dicke in his Einstein day lectures.

Let me first rederive the Dicke paradox. He relies on the empirical fact the the deacceleration parameter today q_0 is of order 1.

$$q_0 \equiv - \ddot{R} \frac{R}{\dot{R}^2}$$

Use the eqs of motion

$$3\ddot{R} = -4\pi G(\rho + 3p)R$$

$$\dot{R}^2 + k = \frac{8\pi G}{3}\rho R^2,$$

so

$$\cancel{q_0 = \frac{\frac{1}{2}(1 + 3p/\rho)}{1 - \frac{3kM_P^2}{8\pi\rho R^2}}}$$

$$\frac{k}{R^2} = \frac{8\pi\rho}{3M_P^2} - H^2 \qquad G = \frac{1}{M_P^2}, \quad H = \frac{\dot{R}}{R}$$

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Inflati … roblems

The stan … vo ways: (1) The early … re causally disconnec … traordinary accuracy … s problem). These pro … nore orders of magnit … then result from a pe … or when the latent hea … elementary-particle ir … uppression. Unfortun … ought.

Inflation and the horizon

The idea of inflation was motivated primarily by the flatness and horizon problems.

Recall the acceleration equation: $$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho(1+3w) \quad ,$$

Clearly, this allows accelerating expansion if w < -1/3, such is the case for a vacuum energy density with w = -1.

Since since ρ is constant (for vacuum energy), we have exponential expansion

$a(t) \propto e^{Ht}$ where $H^2 = \frac{8\pi G\rho_v}{3} = \Lambda/3$

This solves the flatness problem by driving Ω towards 1, and it also solves the horizon problem. The parts of the universe we see were once in contact.

Inflation and the horizon

The inflation theory envisages a massive exponential expansion of the Universe, at t~10^{-36}-10^{-34s}, involving ~100 e-foldings. This enlarges the horizon size at this very early time from ~10^{-27}m to ~1, which is ample to encompass our whole sky. Hence the whole of our visible universe was in causal contact at that time. There is no consensus on the cause of inflation.

But why don't the photons all go away? Inflation should drop the temperature from T = 10^{28} K before inflation to 10^{-15} K after.

At the end of the inflationary epoch, the vacuum energy is released by the decay of the "false vacuum", reheating the universe back to the high temperature at which inflation was initiated. With the decay of the high vacuum energy, the subsequent evolution will initially be radiation-dominated, and the proper radius of the horizon will continue to expand at speed $d(d_{\mathrm{hor}})/dt$ ~2c.

Inflation and the horizon

But why are there still density fluctuations?

Quantum fluctuations of the vacuum state will be blown up to macroscopic sizes by the inflationary episode, and these can form the seeds from which subsequent growth of structure develops. Topological defects (cosmic strings, domain walls etc) have also been proposed as originators of primordial fluctuations.

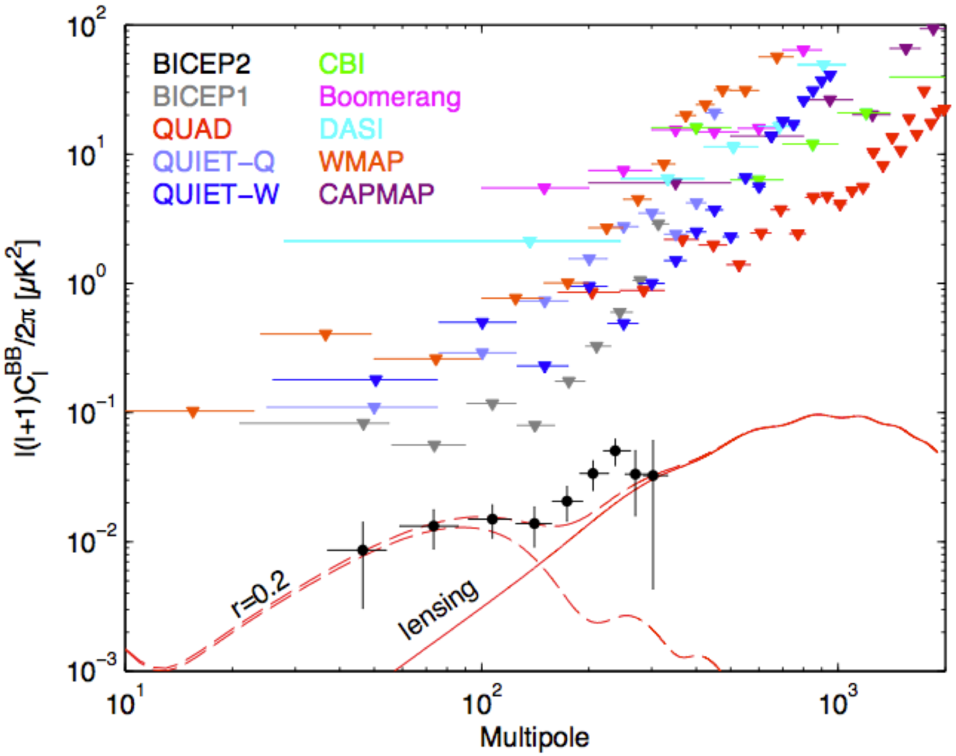
The structure we see in the Universe today was seeded on quantum scales by virtual particles popping in and out of existence.

Gravity waves and Inflation

Quantization of the gravitational field combined with the exponential expansion of inflation should produce a background of gravitational waves.

Though the waves themselves are much too weak to see directly, we may be able to find their imprint on the radiation CMB. The waves induce quadrupole anisotropies in the radiation field, which induce degree scale polarization. This can't be produced from density perturbations.

BICEP2 had claimed a detection of these gravitational wave imprints on the CMB.



Dust!!

Nucleosynthesis

Equilibrium

Equilibrium is maintained until:

$$\Gamma \sim H$$

interaction rate

expansion rate

Nucleosynthesis

Light elements and isotopes – deuterium, helium-3, lithium, helium-4 are not produced inside stars

The early universe should only have protons and neutrons separately. What determines how many protons to neutrons? And assuming all neutrons are in Helium-4, what determines the ratio of H to He?

Nucleosynthesis

Light elements and isotopes – deuterium, helium-3, lithium, helium-4 are not produced inside stars

The early universe should only have protons and neutrons separately. What determines how many protons to neutrons? And assuming all neutrons are in Helium-4, what determines the ratio of H to He?

Three things are important:
- protons are lighter than neutrons
- Free neutrons decay with a half life of 610 seconds
- Stable isotopes exist in which neutron doesn't decay

Nucleosynthesis

Start our exploration when T >> O(MeV) [the nuclear binding energy] – protons and neutrons are free particles in thermal equilibrium (Maxwell-Boltzmann distribution)

$$n_{n,p} = g_{n,p} \left(\frac{m_{n,p} T}{2\pi} \right)^{3/2} \exp\left(-\frac{m_{n,p}}{T} \right)$$

n-p equilibrium: $\frac{n_n}{n_p} = \exp\left(-\frac{\Delta m}{T}\right) = \exp\left(-\frac{1.293\,\mathrm{MeV}}{T}\right)$

While T >> 1.293 MeV, the n/p ratio is ~ 1.

- Electroweak interaction
  - $\nu_e + n \leftrightarrow e^- + p$
  - $\nu_e + p \leftrightarrow e^+ + n$

Nucleosynthesis

- Electroweak interaction
  - $\nu_e + n \leftrightarrow e^- + p$
  - $\nu_e + p \leftrightarrow e^+ + n$

Reactions maintain until: $\Gamma \sim H$

Cross-section: $\sigma_W \sim 10^{-43} \left(\frac{T}{1\,\mathrm{MeV}}\right)^2 \mathrm{cm}^2$

$T \approx 0.8$ MeV ($t \approx 1$ sec) $\Leftrightarrow \Gamma/H \approx 1$

The number density of neutron to protons at freeze-out is:

$$\frac{n_n}{n_p} = \exp\left(-\frac{1.293\,\mathrm{MeV}}{T}\right)$$

$$\frac{n_n}{n_p} = \exp\left(-\frac{1.293\,\mathrm{MeV}}{0.8\,\mathrm{MeV}}\right) \approx \frac{1}{5}$$

Nucleosynthesis

Protons and neutrons can form Helium-4 by:
$p + n \Rightarrow D$;
$D + p \Rightarrow {}^3He$
$D + D \Rightarrow {}^4He$

This can proceed until T = 0.06 MeV.
(t = 340 seconds)

This timescale to cool to this temperature makes the decay of neutrons relevant
(T = 610 seconds)

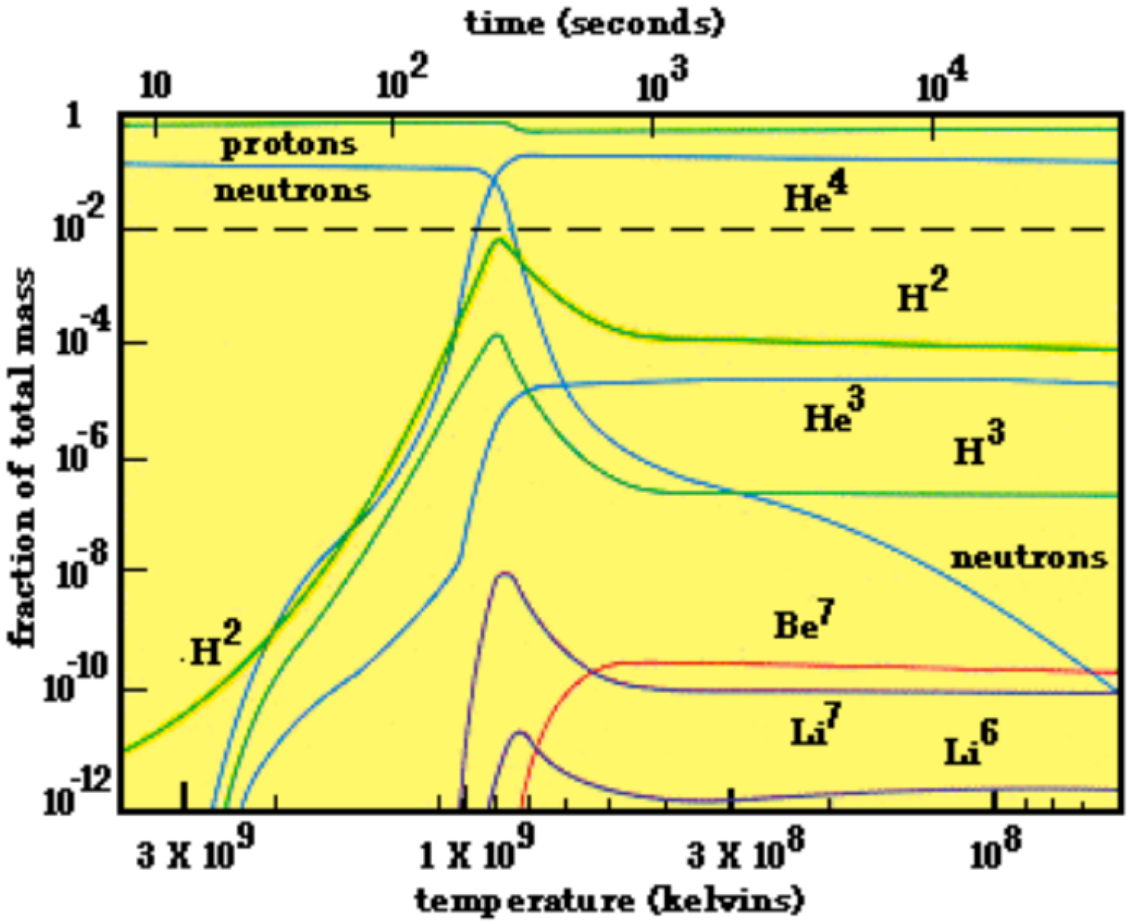
Reduces neutron number density by $e^{(-340s\ \ln 2)/610s}$ So Nn/Np = 1/5 * 0.679 = 1/ 7.3

If the neutron half-life was much shorter, all neutrons would decay and only hydrogen would form.

Assume all neutrons go into He-4, then Y = 2Nn / (Nn + Np) = 0.24.

T < 0.1 MeV

As soon as photon-disintegration of D stops, all other reactions leading to He (and other light elements) take over



The stages of the Universe/baryons

Ionized - The early universe was ionized. And the high scattering cross-section of photons off free elections (σ_T=6.65 × 10^{-29}m^2) means they are tightly coupled.

As the Universe expands and cools, the radiation energy density drops as a^{-4}, whilst the energy density of matter drops only as a^{-3}.

Equality of matter and radiation density – reached at t~50,000 yr.

Recombination – The combining of electrons with nuclei, occurs at t~240,000 yr. Thus, the baryons become neutral.

Decoupling – The radiation (photons) are no longer tightly coupled to baryons. The scattering cross-section of photons off bound elections (away from line transitions) is much lower (t~350,000 yr (z=1100) at T~3000 K).

Last-scattering surface - The CMB photons effectively travel freely from this with their blackbody spectrum cooling from 3000 K to 2.7 K as the universe expands by a factor of 1100.

Reionization – Energetic photons from stars and quasars ionize the diffuse baryons again

Accreted into halos – Form stars/galaxies, are heated by shocks or ejected. Heated outside of dark matter halos.