FRW Universe
&
The Hot Big Bang:

Adiabatic Expansion

From the Friedmann equations, it is straightforward to appreciate that cosmic expansion is an adiabatic process:

$$\dot{\rho} + 3\left(\rho + \frac{p}{c^2}\right)\frac{\dot{a}}{a} = 0$$

$$\Downarrow$$

$$dU = -p\,dV \quad \Longleftarrow \quad \begin{cases} U = \rho c^2 V & \text{internal energy} \\ V \propto a^3 & \text{cosmic volume} \end{cases}$$

In other words, there is no ``external power” responsible for “pumping” the tube …

Adiabatic Expansion

Translating the adiabatic expansion into the temperature evolution of baryonic gas and radiation (photon gas), we find that they cool down as the Universe expands:

$$p \propto \rho^{\gamma} \quad \Longrightarrow \quad T\,V^{\gamma-1} = cst.$$

$$\longrightarrow \begin{cases} \gamma = \frac{5}{3} & \Longrightarrow \quad T_b \propto V^{-2/3} \propto a^{-2} \\ \gamma = \frac{4}{3} & \Longrightarrow \quad T_{rad} \propto V^{-1/3} \propto a^{-1} \end{cases}$$

Adiabatic Expansion

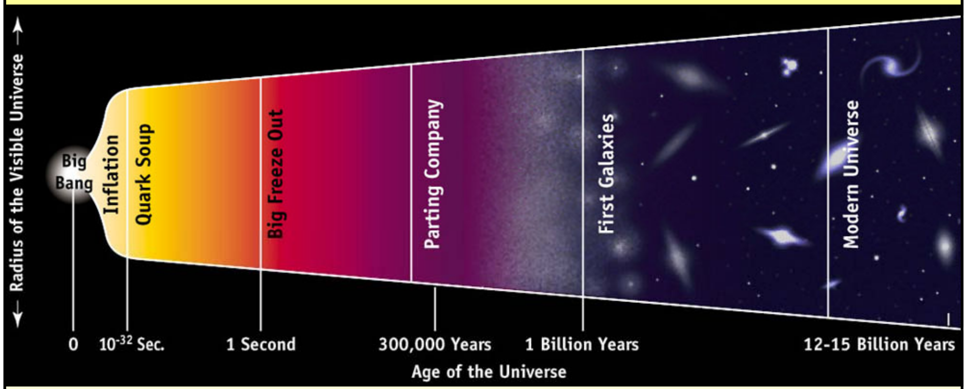
Thus, as we go back in time and the volume of the Universe shrinks accordingly, the temperature of the Universe goes up. This temperature behaviour is the essence behind what we commonly denote as

Hot Big Bang

From this evolution of temperature we can thus reconstruct the detailed

Cosmic Thermal History

The Universe: the Hot Big Bang



Timeline: the Cosmic Thermal History

Equilibrium Processes

Throughout most of the universe's history (i.e. in the early universe), various species of particles keep in (local) thermal equilibrium via interaction processes:

$$\psi_i + \psi_j \rightleftharpoons \chi_k + \chi_k$$

Equilibrium as long as the interaction rate Γ_{int} in the cosmos' thermal bath, leading to N_{int} interactions in time t,

$$\Gamma_{int} \quad \Longrightarrow \quad N_{int}(t) = \int \Gamma_{int}(t)\,dt$$

is much larger than the expansion rate of the Universe, the Hubble parameter H(t):

$$\boxed{\Gamma_{int} \gg H(t)}$$

Brief History of Time

Reconstructing Thermal History Timeline

Strategy:

To work out the thermal history of the Universe, one has to evaluate at each cosmic time which physical processes are still in equilibrium. Once this no longer is the case, a physically significant transition has taken place. Dependent on whether one wants a crude impression or an accurately and detailed worked out description, one may follow two approaches:

- Crudely:

  Assess transitions of particles out of equilibrium, when they decouple from thermal bath. Usually, on crude argument:

$$\boxed{\Gamma_{int} \gg H \quad \longrightarrow \quad \Gamma_{int} < H}$$

- Strictly:

  evolve particle distributions by integrating the Boltzmann equation

Thermal History: Interactions

Particle interactions are mediated by gauge bosons: photons for the electromagnetic force, the W bosons for weak interactions, and gluons for the strong force (and gravitons for the gravitational force). The strength of the interaction is set by the coupling constant, leading to the following dependence of the interaction rate Γ, on temperature T:

(i) mediated by massless gauge boson (photon):

$$\Gamma_{int}/H \sim \alpha^2 m_{Pl}/T$$

α : coupling strength
m_{Pl} : Planck mass

(ii) mediated by massive gauge boson ($W^{+/-}$, Z^0)

$$\Gamma_{int}/H \sim G_x^2\, m_{Pl}\, T^3$$

G_x : coupling strength
m_{Pl} : Planck mass

History of the Universe in Four Episodes: I.

On the basis of the 1) complexity of the involved physics and 2) our knowledge of the physical processes we may broadly distinguish four cosmic episodes:

(I)

Origin universe

???

$t < 10^{-43}$ sec

fundamental physics:

- totally unknown

Planck Era

History of the Universe in Four Episodes: II.

(II)

$10^{-43} < t < 10^{-3}$ sec

VERY early universe

fundamental physics:

- poorly known

- speculative

- Ω_{tot}: curvature/ flatness
- Ω_b (n_b/n_γ)
- `exotic' dark matter
- primordial fluctuations

Products

History of the Universe in Four Episodes: III.

(III)

$10^{-3} < t < 10^{13}$ sec

Standard Hot Big Bang Fireball

fundamental microphysics:

known very well

- primordial nucleo-synthesis
- blackbody radiation: CMB

Products

History of the Universe in Four Episodes: IV.

(IV)

complex macrophysics:

-Fundamentals known

- complex interplay

$t > 10^{13}$ sec

Post (Re)Combination universe

- structure formation:

stars,
galaxies
clusters
…

Products

Episodes Thermal History

Planck Epoch		$t < 10^{-43}$ sec
Phase Transition Era	GUT transition electroweak transition quark-hadron transition	10^{-43} sec $< t < 10^{5}$ sec
Hadron Era		$t \sim 10^{-5}$ sec
Lepton Era	muon annihilation neutrino decoupling electron-positron annihilation primordial nucleosynthesis	10^{-5} sec $< t <$ 1 min
Radiation Era	radiation-matter equivalence recombination & decoupling	1 min $< t <$ 379,000 yrs
Post-Recombination Era	Structure & Galaxy formation Dark Ages Reionization Matter-Dark Energy transition	$t >$ 379,000 yrs

Thermal History: Episode by Episode

Planck Epoch

$t < 10^{-43}$ sec

- In principle, temperature T should rise to infinity as we probe earlier and earlier into the universe's history:

$$T \to \infty, \quad R \downarrow 0$$

- However, at that time the energy of the particles starts to reach values where quantum gravity effects become dominant. In other words, the de Broglie wavelength of the particles become comparable to their own Schwarzschild radius.

Thermal History: Planck Epoch

Once the de Broglie wavelength is smaller than the corresponding Schwarzschild radius, the particle has essentially become a "quantum black hole":

de Broglie wavelength: $\lambda_B = \frac{2h\pi}{mc}$

$\leq$

Schwarzschild radius: $\lambda_S = \frac{2Gm}{c^2}$

These two mass scales define the epoch of quantum cosmology, in which the purely deterministic metric description of gravity by the theory of relativity needs to be augmented by a theory incorporating quantum effects: quantum gravity.

Thermal History: Planck Epoch

On the basis of the expressions of the de Broglie wavelength and the Schwarzschild radius we may infer the typical mass scale, length scale and timescale for this epoch of quantum cosmology:

$$m_{Pl} \equiv \sqrt{\frac{\hbar c}{G}} \sim 10^{19}\,\mathrm{GeV}$$ Planck Mass

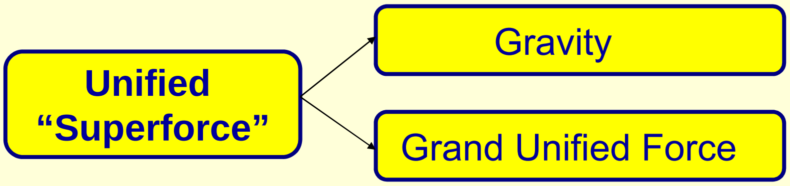
$$l_{Pl} \equiv \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35}\,\mathrm{m}$$ Planck Length

$$t_{Pl} \equiv \sqrt{\frac{\hbar G}{c^5}} \sim 10^{-43}\,\mathrm{sec}$$ Planck Time

Because our physics cannot yet handle quantum black holes, i.e. because we do not have any viable theory of quantum gravity we cannot answer sensibly questions on what happened before the Planck time. In other words, we are not able to probe the ultimate cosmic singularity … some ideas of how things may have been do exist …

Planck Transition

- In the Planck epoch, before the universe is 1 hundred-million-trillion-trillionth (10^{-44}) sec old, the density reaches values higher than $\rho \sim 10^{94}\,\mathrm{g/cm^3}$ and temperatures in excess of $T \sim 10^{32}\,\mathrm{K}$.
- Quantum fluctuations of spacetime, on the scale of the Planck scale and Planck time are now of cosmic magnitude. Space and time are inextricably and discontinuously. As was pictured by J. Wheeler, spacetime under these conditions looks like a chaotic foam.
- Spacetime is a foam of quantized black holes, and space and time no longer exist in the sense that we would understand. There is no "now" and "then", no "here" and "there", for everywhere is torn into discontinuities.
- Then, due to the cosmic expansion, temperatures drop below $T \sim 10^{32}\,\mathrm{K}$, and the unified "superforce" splits into a force of Gravity and a GUT force



Thermal History: Episode by Episode

Phase Transition Era

10^{-43} sec < t < 10^{-5} sec

- The universe is filled by a plasma of relativistic particles:

  quarks, leptons,
  gauge bosons, Higgs bosons, ...

- During this epoch, as the universe expands and cools down, it undergoes various phase transitions, as a result of

Spontaneous Symmetry Breaking

Thermal History: Episode by Episode

Phase Transition Era

10^{-43} sec < t < 10^{-5} sec

- We may identify three major phase transitions during this era:

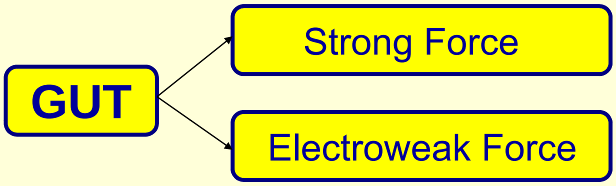
◊	GUT transition	$z \sim 10^{27}$-10^{29}
◊	Electroweak transition	$z \sim 10^{15}$
◊	Quark-Hadron transition	$z \sim 10^{11}$-10^{12} ($t \sim 10^{-5}$s)

GUT Transition

$T \sim 10^{14} – 10^{16}$ GeV
$\sim 10^{27} – 10^{29}$ K
$z \sim 10^{27} – 10^{29}$

- Before this transition, at $T > 10^{14}$-10^{16} GeV, there was one unified GUT force, i.e. strong, weak and electromagnetic force equally strong (note: gravity is a different case).
- Also, the universe did not have a net baryon number (as many baryons as antibaryons).
- At the GUT transition, supposedly through the Higgs mechanism, the unified GUT force splits into forces, the strong force and the electroweak force:

GUT Transition



- Baryon non-conserving processes

  It is possible that the origin of the present-day excess of matter over antimatter finds its origin in the GUT phase transition.

- Inflationary Epoch

  It is conceivable that the GUT transition may be identified with the phase transition that gave rise to a rapid exponential de Sitter expansion, in which the universe expanded by ~ 60 orders of magnitude (and in which its horizon shrank accordingly). Primordial density perturbations, the seeds of cosmic structure, may have been generated during this episode.

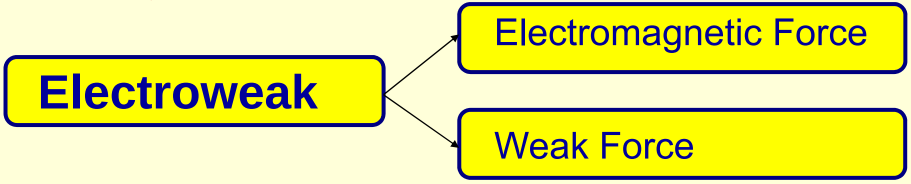
Electroweak Transition

T ~ 300 GeV

~ 3 x 10^{15} K

z ~ 10^{15}

- At this energy scale, the electroweak force splits into the electromagnetic force and the weak force .



Electroweak

Electromagnetic Force

Weak Force

- All the leptons acquire masses (except possibly neutrinos), intermediate vector bosons give rise to massive bosons W^+, W^- and Z^o, and photons.

Quark-Hadron Transition

T ~ 0.2 GeV

~ 10^{12} K

t ~ 10^{-5} sec

- Above this temperature, matter in the universe exists in the form of a quark-gluon plasma. Below this temperature, isolated quarks cannot exist, and become confined in composite particles called hadrons. They combine into (quark confinement):

◊ baryons	quark triplet
◊ mesons	quark-antiquark pairs

- Also, 1) QCD chiral symmetry breaking
  2) axion acquires mass
  (axion: most popular candidate for Cold Dark Matter)

Thermal History: Episode by Episode

Hadron Era

$t \sim 10^{-5}$ sec; $300 > T > 130$ MeV

- The hadrons formed during the quark-hadron transition are usually short-lived particles (except for protons & neutrons). Therefore, there is only a brief period in which the hadrons flourish.
- Although called "Hadron Era", hadrons do not dominate the energy density.
- Pion-pion interactions are very important. Towards the end of hadron era, π^+ and π^- annihilate, π^0 decay into photons.

Thermal History: Episode by Episode

Lepton Era

10^{-5} sec $< t < 1$ min

$130 > T > 0.5$ MeV 10^{12} K $> T > 5 \times 10^9$ K

- At the beginning of the lepton era, the universe comprises:
  - ◊ photons,
  - ◊ baryons (small number)
  - ◊ leptons: electrons & positrons e^-, e^+, muons μ^+, μ^-, tau's τ^+ and τ^-
    electron, muon and tau neutrino's

Thermal History: Episode by Episode

Lepton Era

10^{-5} sec < t < 1 min;

130 > T > 0.5MeV 10^{12} K > T > 5×10^{9} K

- Four major events occur during the lepton era:

◊ Annihilation muons	T ~ 10^{12} K	
◊ Neutrino Decoupling	T ~ $10^{10.5}$ K; z ~ 10^{10}	
◊ Electron-Positron Annihilation	T < 10^{9} K;	z ~ 10^{9}, t~1 min
◊ Primordial Nucleosynthesis	T ~10^{9} K;	t ~ 200 sec (3 min)

Neutrino Decoupling

T ~ $10^{10.5}$ K

t ~ 10^{-5} sec, z ~ 10^{10}

- Weak interactions, e.g.

$$e^{+} + e^{-} \rightleftharpoons \nu + \bar{\nu}$$

get so slow that neutrinos decouple from the e^{+}, e^{-}, γ plasma. Subsequently, they proceed as a relativistic gas with its own temperature T_ν.

- Because they decouple before the electron-positron annihilation, they keep a temperature T_ν which is lower than the photon temperature T_γ (which gets boost from released annihilation energy):

$$\boxed{T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.95\ \mathrm{K}}$$

- The redshift of neutrino decoupling, z~10^{10}, defines a surface of last neutrino scattering, resulting in a "Cosmic Neutrino Background" with present-day temperature T~1.95 K. A pity it is technically not feasible to see it !

Electron-Positron Annihilation

$T < 10^9$ K

$t \sim 1$ min, $z \sim 10^9$

- Before this redshift, electrons and photons are in thermal equilibrium. After the

$$e^+ + e^- \rightleftharpoons 2\gamma$$

temperature drops below $T \sim 10^9$ K, the electrons and positrons annihilate, leaving a sea of photons.

- As they absorb the total entropy s of the e^+, e^-, γ plasma, the photons acquire a temperature $T_\gamma >$ neutrino temperature T_ν .

Electron-Positron Annihilation

$T < 10^9$ K

$t \sim 1$ min, $z \sim 10^9$

At this redshift the majority of photons of the Cosmic Microwave Background are generated.

- These photons keep on being scattered back and forth until $z \sim 1089$, the epoch of recombination.
- Within 2 months after the fact, thermal equilibrium of photons is restored by a few scattering processes:
  - free-free scattering
  - Compton scattering
  - double Compton scattering

The net result is the perfect blackbody CMB spectrum we observe nowadays.

Primordial Nucleosynthesis

T ~ 10^9 K ~ 0.1 MeV

t ~ 200 sec ~ 3 min

- At the end of these "first three minutes" we find an event that provides us with the first direct probe of the Hot Big Bang, the nucleosynthesis of the light chemical elements, such as deuterium, helium and lithium.
- The prelude to this event occurs shortly before the annihilation of positrons and electrons. The weak interactions coupling neutrons and protons

$$p + e^- \rightleftharpoons n + \nu$$
$$p + \bar{\nu} \rightleftharpoons n + e^+$$

can no longer be sustained when the temperature drops below T ~ 10^9 K, resulting in a

Freeze-out of Neutron-Proton ratio:

$$\boxed{\frac{N_n}{N_p} \approx \frac{1}{6}}$$

Primordial Nucleosynthesis

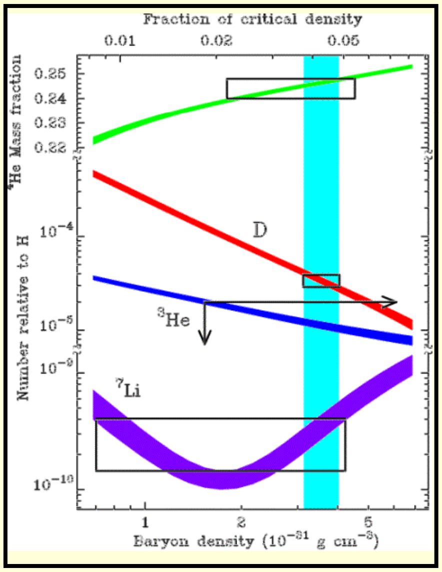
- Note that from the ratio N_n/N_p ~ 1/6 we can already infer that if all neutrons would get incorporated into ^{4}He nuclei, around 25% of the baryon mass would involve Helium ! Not far from the actual number ...

- After freeze-out of protons and neutrons, a number of light element nucleons forms through a number of nuclear reactions involving the absorption of neutrons and protons:

• Deuterium	$n + p \rightleftharpoons \mathrm{D} + \gamma$
• ^{3}He	$\mathrm{D} + p \rightleftharpoons {}^3\mathrm{He}$
• ^{4}He	${}^3\mathrm{He} + n \rightleftharpoons {}^4\mathrm{He}$

- and traces of ^{7}Li and ^{9}Be

Primordial Nucleosynthesis



- Heavier nuclei will not form anymore, even though thermodynamically preferred at lower temperatures: when 4He had formed, the temperature and density have simply below too low for any significant synthesis.
- The precise abundances of the light elements depends sensitively on various cosmological parameters.
- Particularly noteworthy is the dependence on the ratio of baryons to photons (proportional to the entropy of the universe), setting the # neutrons and protons available for fusion:

$$\eta \equiv \frac{n_B}{n_\gamma}$$

- By comparing the predicted abundances as function of η, one can infer the density of baryons in the universe, Ω_B (see figure).

Primordial Nucleosynthesis

- On the basis of the measured light element abundances, we find a rather stringent limit on the baryon density in the universe:

$$\boxed{0.005 \lesssim \Omega_b h^2 \lesssim 0.026}$$

- This estimate of the baryon density from primordial nucleosynthesis is in perfect agreement with the completely independent estimate of the baryon density from the second peak in the angular power spectrum of the WMAP temperature perturbations:

$$\Omega_b h^2 \approx 0.0224 \pm 0.0009$$
$$\Omega_b \approx 0.044 \pm 0.004$$

- This should be considered as a truly astonishing vindication of the Hot Big Bang.
- Not that these nuclear reactions also occur in the Sun, but at a considerably lower temperature: T ~ 1.6 x 10^7 K. The fact that they occur in the early universe only at temperatures in excess of 10^9 K is due to the considerably lower density in the early universe:

$$\rho_{\odot,centre} \approx 10^2 \ \mathrm{g\,cm^{-3}}$$
$$\rho_{univ,t-3min} \approx 10^{-8} \ \mathrm{g\,cm^{-3}}$$

Thermal History: Episode by Episode

Radiation Era

$t > 1$ min; $T < 5 \times 10^9$ K

- The radiation era begins at the moment of annihilation of electron-positron pairs.
- After this event, the contents of the universe is a plasma of photons and neutrinos, and matter (after nucleosynthesis mainly protons, electrons and helium nuclei, and of course the unknown "dark matter").
- During this era, also called "Plasma Epoch", the photons and baryonic matter are glued together. The protons and electrons are strongly coupled by Coulomb interactions, and they have the same temperature. The electrons are coupled to the radiation by means of Compton scattering. Hence, baryons and radiation are in thermal equilibrium.

Thermal History: Episode by Episode

Radiation Era

$t > 1$ min; $T < 5 \times 10^9$ K

- Two cosmic key events mark the plasma era:

◊	Radiation-Matter transition (equivalence matter-radiation)	$z_{eq} \sim 2 \times 10^4$
◊	Recombination & Decoupling	$z \sim 1089$; $t \sim 279{,}000$ yrs

Radiation-Matter Equality

$z_{eq} \sim 2 \times 10^4$

- The time of matter-radiation equality represents a crucial dynamical transition of the universe.
- Before z_{eq} the dynamics of the universe is dominated by Radiation. After equivalence Matter takes over as the dominant component of the universe.

$$z > z_{eq}: \qquad \rho_{rad} > \rho_m$$
$$z < z_{eq}: \qquad \rho_{rad} < \rho_m$$

- Because the energy density of radiation diminishes with the fourth power of the expansion of the universe, while the density of matter does so with the third power, the ratio between radiation and matter density is an increasing function of a(t):

$$\rho_{rad} \propto a(t)^{-4} \leftrightarrow \rho_m \propto a(t)^{-3}$$
$$\Downarrow$$
$$\frac{\rho_m}{\rho_{rad}} = 4.3 \times 10^4\, \Omega_m h^2 \frac{1}{1+z}$$

Radiation-Matter Equality

- The redshift z_{eq} at which the radiation and matter density are equal to each other can then be inferred:

$$1 + z_{eq} = 4.0 \times 10^4\ \Omega_m h^2$$

- Because of the different equation of state for matter and radiation (and hence their different density evolution), the universe changes its expansion behaviour:

• radiation-dominated	$z > z_{eq}:$	$a(t) \propto t^{1/2}$
• matter-dominated	$z < z_{eq}:$	$a(t) \propto t^{2/3}$

- This has dramatic consequences for various (cosmic structure formation) processes, and we can find back the imprint of this cosmic transition in various phenomena.
- Note that the universe underwent a similar transition at a more recent date. This transition, the "Matter-Dark Energy Equality" marks the epoch at which dark energy took over from matter as dynamically dominant component of the universe.

Recombination Epoch

T ~ 3000 K

z_{dec}=1089 (Δz_{dec}=195); t_{dec}=379.000 yrs

- Before this time, radiation and matter are tightly coupled through bremsstrahlung:

$$\boxed{e^- + \gamma \rightleftharpoons e^- + \gamma}$$

Because of the continuing scattering of photons, the universe is a "fog".

- A radical change of this situation occurs once the temperature starts to drop below T~3000 K. and electrons. Thermodynamically it becomes favorable to form neutral (hydrogen) atoms H (because the photons can no longer destory the atoms):

$$\boxed{p + e^- \rightleftharpoons \mathbf{H}}$$

- This transition is usually marked by the word "recombination", somewhat of a misnomer, as of course hydrogen atoms combine just for the first time in cosmic history. It marks a radical transition point in the universe's history.

Recombination Epoch

- This happened 279,000 years after the Big Bang, according to the impressively accurate determination by the WMAP satellite (2003).
- Major consequence of recombination:

Decoupling of Radiation & Matter

- With the electrons and protons absorbed into hydrogen atoms, the Photons decouple from the plasma, their mean free path becoming of the order of the Hubble radius. The cosmic "fog" lifts:

universe transparent

- The photons assume their long travel along the depths of the cosmos. Until some of them, Gigaparsecs further on and Gigayears later, are detected by telescopes on and around a small planet in some faraway corner of the cosmos …

Recombination & Decoupling

- In summary, the recombination transition and the related decoupling of matter and radiation defines one of the most crucial events in cosmology. In a rather sudden transition, the universe changes from

Before z_{dec}, $z>z_{dec}$

- universe fully ionized
- photons incessantly scattered
- pressure dominated by radiation:

$$p = \frac{1}{3} a T^4$$

After z_{dec}, $z<z_{dec}$

- universe practically neutral
- photons propagate freely
- pressure only by baryons:

$$p = n\,k\,T$$

- (photon pressure negligible)

Recombination & Decoupling

- Note that the decoupling transition occurs rather sudden at T~3000 K, with a "cosmic photosphere" depth of only Δz_{dec}~195 (at z~1089).
- The cosmological situation is highly exceptional. Under more common circumstances the (re)combination transition would already have taken place at a temperature of $T \sim 10^4$ K.
- Due to the enormous amount of photons in the universe, signified by the abnormally high cosmic entropy,

$$\boxed{\frac{n_\gamma}{n_B} \approx 10^9}$$

even long after the temperature dropped below $T \sim 10^4$ K there are still sufficient photons to keep the hydrogen ionized (i.e. there are still plenty of photons in the Wien part of the spectrum).

- Recombination therefore proceeds via a 2-step transition, not directly to the groundstate of hydrogen. The process is therefore dictated by the rate at which Lyα photons redshift out of the Lyα rest wavelenght. For $n_\gamma/n_B \sim 10^9$ this occurs at

$$\boxed{T \sim 3000\,\mathrm{K}}$$

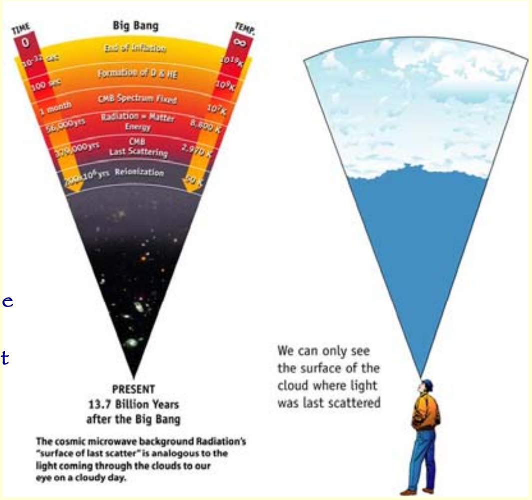
Recombination Epoch

- The photons that are currently reaching us, emanate from the

Surface of Last Scattering

located at a redshift of z~1089.

- The WMAP measurement of the redshift of last scattering confirms the theoretical predictions (Jones & Wyse 1985) of a sharply defined last scattering surface.
- The last scattering surface is in fact somewhat fuzzy, the photons arrive from a "cosmic photosphere" with a narrow redshift width of Δz~195.



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

Recombination Epoch

- The photons emanating from the last scattering surface, freely propagating through our universe, define a near isotropic sea of radiation.
- Shortly after they were created at the time of electron-positron annihilation, z ~10^9, the photon bath was thoroughly thermalized. It thus defines a most perfect blackbody radiation field:

$$I_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

- Due to the cosmic expansion, the radiation field has in the meantime cooled down to a temperature of T=2.725 K (+/- 0.002 K, WMAP).
- This cosmic radiation we observe as the

Cosmic Microwave Background

Recombination Epoch

Cosmic Microwave Background

- first discovered serendipitously by Penzias & Wilson in 1965, and reported in their publication "… an excess measurement …", without doubt should be regarded as one of the principal scientific discoveries of the 20th century.
- Its almost perfect blackbody spectrum is the ultimate proof of a hot and dense early phase:

the Hot Big Bang

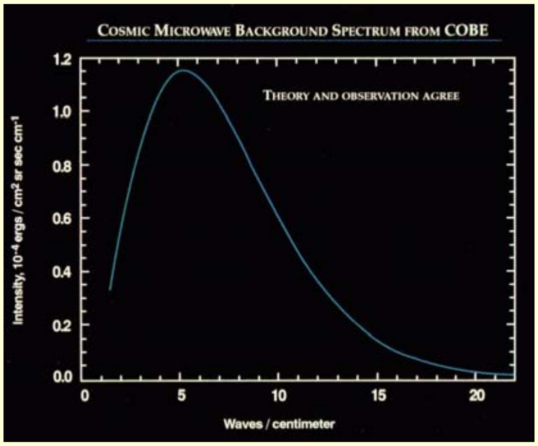
… the Nobel prize for the discovery of the CMB followed in 1978 …

Recombination Epoch

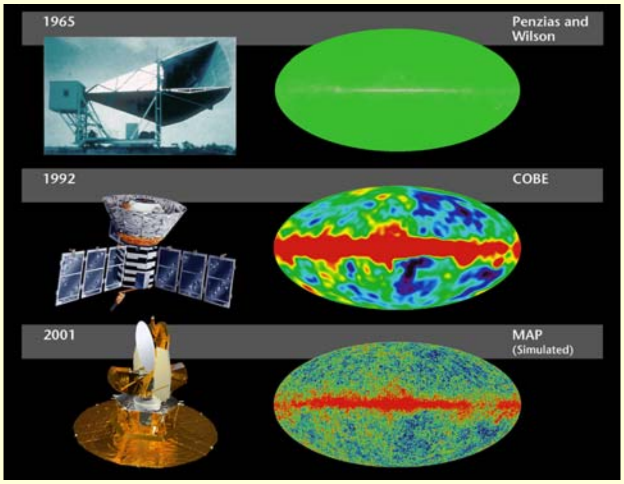
Cosmic Microwave Background

- The amazingly precise blackbody nature of the CMB was demonstrated by the COBE satellite (1992).
- The spectral energy distribution in the figure is so accurately fit by a Planckian spectrum that the error bars are smaller than the thickness of the solid (blue) curve (see figure) !!!
- Note that the corresponding CMB photon number density is:

$$\boxed{n_\gamma \sim 410\,\mathrm{cm}^{-3}}$$



Cosmic Microwave Background



The CMB is a fabulously rich treasure trove of information on the primordial universe.

In the accompanying figure you see three milestones of CMB research:

1) The discovery of the CMB by Penzias & Wilson in 1965.

2) The COBE satellite (1992), first discovery of primordial perturbations.

3) WMAP (2003), detailed temperature perturbations "fix" the universe's parameters.

Opening View onto the Primordial Universe

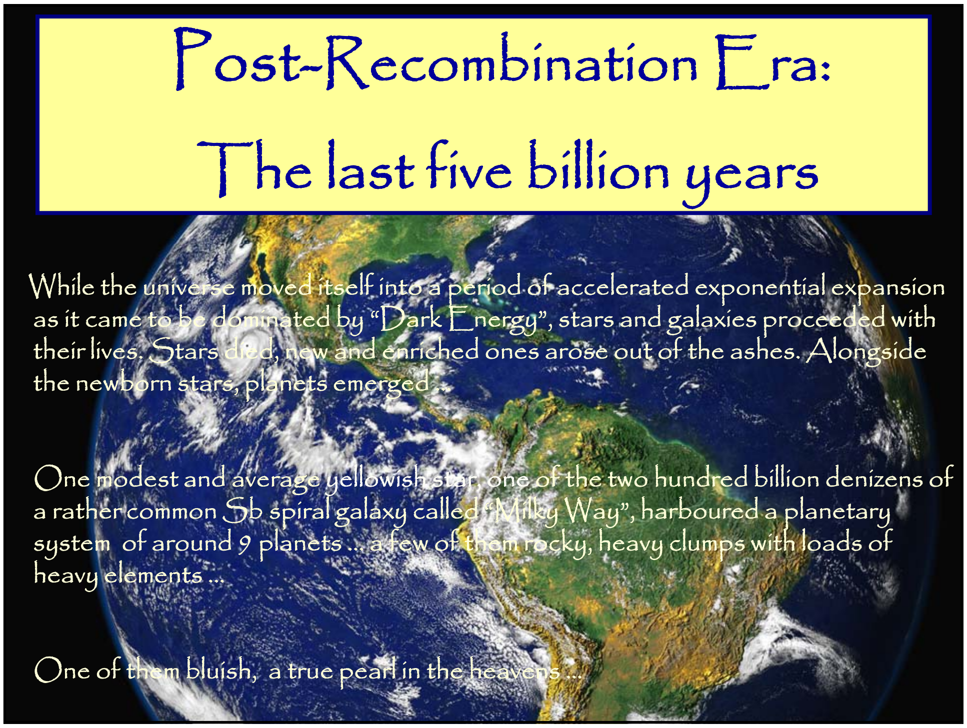
Thermal History: Episode by Episode

Post-Recombination Era

t > 279,000 yrs; T < 3000 K

After recombination/decoupling, while the universe expands it gradually cools down (baryonic matter faster than radiation once they are entirely decoupled). We can identify various major processes and transitions during these long-lasting eons ...

◊	Structure & Galaxy Formation	z ~ 1089-0
◊	Dark Ages	z ~ 1089-10/20
◊	Reionization	z ~ 20-6 ?
◊	Matter-Dark Energy transition	z ~ 0.3

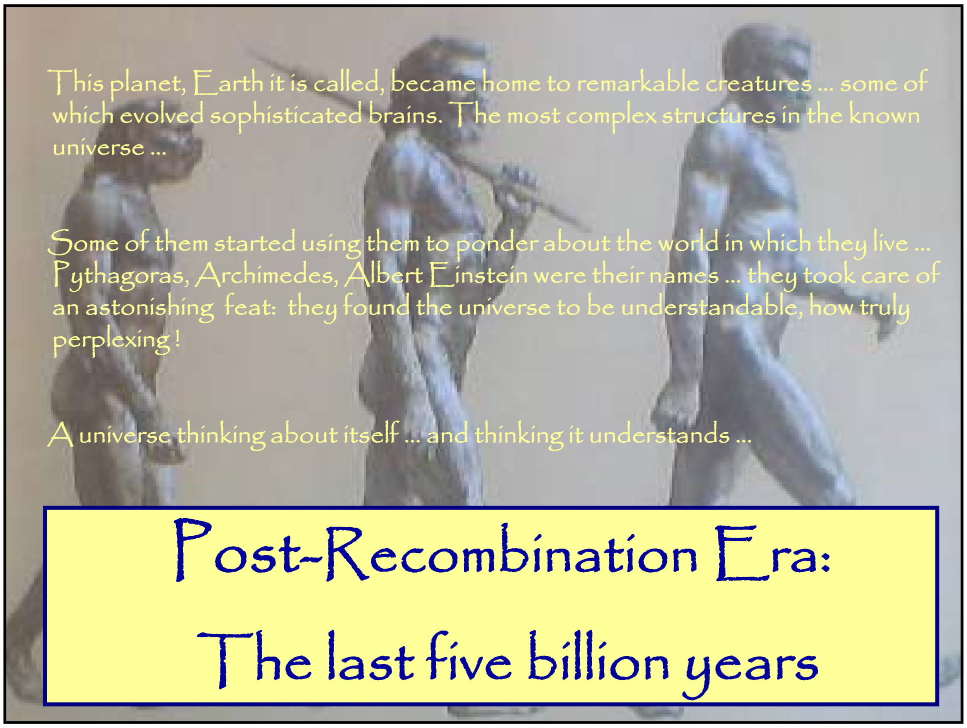


Post-Recombination Era:
The last five billion years

While the universe moved itself into a period of accelerated exponential expansion as it came to be dominated by "Dark Energy", stars and galaxies proceeded with their lives. Stars died, new and enriched ones arose out of the ashes. Alongside the newborn stars, planets emerged ...

One modest and average yellowish star, one of the two hundred billion denizens of a rather common Sb spiral galaxy called "Milky Way", harboured a planetary system of around 9 planets ... a few of them rocky, heavy clumps with loads of heavy elements ...

One of them bluish, a true pearl in the heavens ...



This planet, Earth it is called, became home to remarkable creatures ... some of which evolved sophisticated brains. The most complex structures in the known universe ...

Some of them started using them to ponder about the world in which they live ... Pythagoras, Archimedes, Albert Einstein were their names ... they took care of an astonishing feat: they found the universe to be understandable, how truly perplexing !

A universe thinking about itself ... and thinking it understands ...

Post-Recombination Era:
The last five billion years