Hot or cold universe??

Any signatures of the past around us?

**Microwave background radiation!**

George Gamow (lived 1904--1968) predicted in 1948 that there should be a faint glow left over from when the universe was much hotter and denser. The entire universe would have glowed first in the gamma ray band, then the X-ray band, then to less energetic bands as the universe expanded. By now, about 14 billion years after the start of the expansion, the cold universe should glow in the radio band.
George Gamow

Born 1904 in Russia
Studied and worked at St.-Petersburg University
Fled Russia in 1934
Worked at GW University and University of Colorado

Proposed the concept of the Hot Big Bang
Explained the origin of chemical elements in the universe
Built the theory of radioactivity and explained the nucleosynthesis in stars
Proposed a concept of genetic code and explained how the code is implemented in DNA by the order of nucleotides

The cosmogenesis paper with Alpher ("The origin of chemical elements") was published as the Alpher-Bethe-Gamow theory, Gamow had added the name of Hans Bethe to make a pun on the first three letters of the Greek alphabet, *alpha beta gamma*. 
Consider that the Pressure was highest during the early Universe when photons were “coupled” to all the baryons. For relativistic particles:

\[ R^4 \rho_{\text{rel}} = \rho_{\text{rel},0} \]

compare this to, for matter:

\[ R^3 \rho_m = \rho_{m,0} \]

Transition point when the density from photons was greater than matter was the transition from a **matter era** to a **radiation era**.
COSMIC MICROWAVE BACKGROUND

Transition from the Radiation Era to the Matter Era

WMAP can actually estimate this experimentally, and it gives:

\[ [z_{r,m}]_{\text{WMAP}} = 3233^{+194}_{-210} \]

And we can work out what the temperature of the Universe was:

\[ T_{r,m} = \frac{T_0}{R_{r,m}} = 6.56 \times 10^4 \Omega_{m,0} h^2 K = 8920 K \text{ for WMAP values} \]

Note linear dependence:

\[ T = \frac{T_0}{R} \]
Today $t_0$
- Life on earth
- Solar system
- Quasars

**Galaxy formation**
- Epoch of gravitational collapse

**Recombination**
- Relic radiation decouples (CBR)

**Matter domination**
- Onset of gravitational instability

**Nucleosynthesis**
- Light elements created: D, He, Li

**Quark-hadron transition**
- Hadrons form: protons & neutrons

**Electroweak phase transition**
- Electromagnetic & weak nuclear forces become differentiated

$t_0 \sim 14$ Gyr

$t \sim 55,000$ yr

$z \sim 3000$

$z \sim 1000$
Origin of CMB

Calculate where the average time between photon scatterings by electrons approaches the timescale of the expansion:

$$\tau_{\text{exp}}(t) = \left( \frac{1}{R(t)} \frac{dR(t)}{dt} \right)^{-1} = \frac{1}{H(t)}$$

At times greater than this, the photons were **decoupled** from the matter. If electrons had remained free decoupling would have occurred when the Universe was 20 Myr old. But when the Universe was 1 Myr, electrons combined (we call this **recombination**) with protons and He-4 nuclei and the photon opacity dropped to zero.

**Surface of Last Scattering**

was the point from where the CMB photons are now arriving. It is the farthest redshift we can see (in reality there is a thickness to this “surface”).
Protons and electrons recombine to form atoms => universe becomes transparent for photons

\[ z \approx 3000 \]
\[ z \approx 1000 \]

Dark energy dominates

Transition to matter dominated era
The Cosmic Background Radiation

After recombination, photons can travel freely through space.

Their wavelength is only stretched (red shifted) by cosmic expansion.

Recombination:

$z = 1000; \ T = 3000 \ K$

This is what we can observe today as the cosmic background radiation!
The present universe as it appears from our galaxy
Origin of CMB

Surface of Last Scattering

was the point from where the CMB photons are now arriving. It is the farthest redshift we can see (in reality there is a thickness to this “surface”).

Conditions for Recombination can be estimated from the Saha equation.

\[
\frac{N_{\text{II}}}{N_{\text{I}}} = \frac{2Z_{\text{II}}}{n_{e}Z_{\text{I}}} \left( \frac{2\pi m_{e}kT}{h^2} \right)^{3/2} e^{-\chi_{\text{I}}/kT}
\]

Assuming (incorrectly) pure hydrogen gas, \(Z_{\text{II}}=1\) and \(Z_{\text{I}} = 2\). We will also define \(f\) as the fraction of ionized hydrogen atoms,

\[
f = \frac{N_{\text{II}}}{N_{\text{I}}} = \frac{N_{\text{II}}}{N_{\text{I}}} = \frac{N_{\text{II}}/N_{\text{I}}}{(1 + N_{\text{II}}/N_{\text{I}})}
\]

or \(N_{\text{II}} / N_{\text{I}} = f / (1 - f)\).

For ionized hydrogen there is one free electron for every proton, \(n_{e} = n_{p}\):

\[
n_{e} = n_{p} = f(n_{p} + n_{H}) = f\rho_{b} / m_{H}
\]
Origin of CMB

Surface of Last Scattering

For ionized hydrogen there is one free electron for every proton, \( n_e = n_p \):

\[
n_e = n_p = f(n_p + n_H) = f\rho_b / m_H
\]

One can write the electron density in the expansion as, \( n_e(R) = f\rho_b / m_H R^3 \)

Inserting all this into the Saha equation gives:

\[
\frac{f}{1 - f} = \frac{m_H R^3}{f\rho_{b,0}} \left( \frac{2\pi m_e kT_0}{h^2 R} \right)^{3/2} e^{-\chi_I R/kT_0}
\]

where \( T_0 = 2.725 \, \text{K} \) and \( \chi_I = 13.6 \, \text{eV} \) (just like for stellar atmospheres). This can be solved to find that \( f = 0.5 \) when \( R \sim 7.3 \times 10^{-4} \) which occurs for \( z = 1380 \) and \( T = 3760 \, \text{K} \).

WMAP finds the following:

\[
[z]_{\text{WMAP}} = 1089 \pm 1 \quad \quad T_{\text{dec}} = T_0 (1 + z_{\text{dec}}) = 2970 \, \text{K}
\]

which corresponds to an age for the Universe of

\[
[t_{\text{dec}}]_{\text{WMAP}} = 379^{+8}_{-7} \, \text{kyr}
\]
CMB temperature

Key idea of “Big Bang” was that the early Universe was very hot and dense. For an ultrarelativistic gas (or radiation) we can use the energy density for a blackbody: \( u = aT^4 \). The energy density evolves in an expanding Universe by:

\[
R^3(1+w)u = R^4u = u_0
\]

where \( w = 1/3 \) for blackbody radiation (\( w = 0 \) for “pressureless” dust).

The energy density today is much, much smaller by a factor of \( R^4 \). A factor of \( R^3 \) is due to the change in the volume and another factor of \( R \) is due to the expansion of the wavelength of light.

Thus, \( R^4aT^4 = aT_0^4 \) and we find that the blackbody temperature must be related to the temperature at an earlier time as \( RT = T_0 \).
The Cosmic Background Radiation

The radiation from the very early phase of the universe should still be detectable today

Was, in fact, discovered in mid-1960s as the Cosmic Microwave Background:

Blackbody radiation with a temperature of $T = 2.73$ K
Arno Penzias and Robert Wilson observed in 1965 a radio background source that was spread all over the universe---the **cosmic microwave background radiation**. The radiation has the same intensity and spectral character as a thermal continuous source at 3 K (more precisely, 2.728 ± 0.004 K) as measured by the COBE satellite in every direction observed. To a high degree of precision the sky is *uniformly* bright in radio. The uniformity of the background radiation is evidence for the cosmological principle.

From 3000 K to 2.7 K:
The redshift of 1000!

Penzias and Wilson received the Nobel Prize in 1978. John Mather received the Nobel Prize in 2006.
Our current measurements of the CMB come from WMAP, the Wilkinson Microwave Anisotropy Probe.

Launched in 2001, it was designed to study the slight fluctuations in left in the CMB (more on this). It has confirmed small details of the Big Bang. It also gives us the best measurement of $H_0$:

$$H_0 = 71 \ (\pm 4/-3) \ \text{km/s/Mpc}$$

This gives us a current Hubble time of:

$$t_H = 1/H_0 = 4.35 \times 10^{17} \text{ s} = 1.38 \times 10^{10} \text{ yr}.$$
The Big Bang happened everywhere. So the CMB comes from everywhere! For this reason all observers at rest with respect to the expansion of the Universe see the same spectrum.

Turns out, the Milky Way (and thus we) are moving with respect to the expansion. This produces a small shift in the CMB spectrum from our Doppler motion.

The temperature of the CMB we measure has a dependence on where you look:

\[ T_{\text{moving}} = \frac{T_{\text{rest}} \sqrt{1 - \frac{v^2}{c^2}}}{1 - \left(\frac{v}{c}\right) \cos \theta} \]

or for \( v \ll c \):

\[ T_{\text{moving}} \approx T_{\text{rest}} \left(1 + \frac{v}{c} \cos \theta\right) \]
Redder shades are slightly hotter (we are moving toward that direction) and blue are slight cooler.

**Particle Era**
Elementary particles filled the universe; then quarks combined to make protons and antiprotons.

**Era of Nucleosynthesis**
Fusion produced helium from protons (H nuclei).

**Era of Nuclei**
A plasma of free electrons and H and He nuclei filled the universe.

**Era of Atoms**
The era of atoms lasted until stars and galaxies began to form.

- **Protons annihilated virtually all antiprotons,** but some protons remained.

- **Fusion ceased,** leaving normal matter 75% hydrogen and 25% helium by mass.

- **Neutral atoms formed,** allowing photons to travel freely through space.
For reasons not quite understood, there was a very slight excess of ordinary matter over antimatter (by about 1 part in $10^9$). This is why there was still some ordinary matter left over when all the antimatter had been annihilated. (This must be the case, otherwise you wouldn't be here!) All of the protons, neutrons, and electrons in matter today were created in the first few seconds after the Big Bang.
Protons and neutrons form a few helium nuclei; the rest of protons remain as hydrogen nuclei.

25% of mass in helium, 75% in hydrogen.

No stable nuclei with 5 and 8 protons.

Almost no elements heavier than helium are produced.
Cosmic Abundance of Helium and Hydrogen
The Big Bang theory provides a natural way to explain the present abundance of the elements. At about 2 to 3 minutes after the Big Bang, the expanding universe had cooled to below about $10^9$ K so that protons and neutrons could fuse to make stable deuterium nuclei (a hydrogen isotope with one proton and one neutron) that would not be torn apart by energetic photons. Protons react to produce deuterium, deuterium nuclei react to make Helium-3 nuclei, and Helium-3 nuclei react to make the stable Helium-4 nucleus.

The deuterium nucleus is the weak link of the chain process, so the fusion chain reactions could not take place until the universe had cooled enough. The exact temperature depends sensitively on the density of the protons and neutrons at that time. Extremely small amounts of Lithium-7 were also produced during the early universe nucleosynthesis process. After about 15 minutes from the Big Bang, the universe had expanded and cooled so much that fusion was no longer possible. The composition of the universe was 10% helium and 90% hydrogen (or if you use the proportions by mass, then the proportions are 25% helium and 75% hydrogen). Except for the extremely small amounts of the Lithium-7 produced in the early universe, the elements heavier than helium were produced in the cores of stars.
The Nature of Dark Matter

Can dark matter be composed of *normal matter*?

- If so, then its mass would mostly come from protons and neutrons = baryons
- The density of baryons right after the big bang leaves a unique imprint in the abundances of deuterium and lithium.
- Density of baryonic matter is only ~ 4 % of critical density.
- Most dark matter **must** be non-baryonic!
Observations are consistent with Hot Big Bang Model

The cosmic microwave background radiation can be explained only by the Big Bang theory. The background radiation is the relic of an early hot universe. The Big Bang theory's major competitor, called the Steady State theory, could not explain the background radiation, and so fell into disfavor.

The amount of activity (active galaxies, quasars, collisions) was greater in the past than now. This shows that the universe does evolve (change) with time. The Steady State theory says that the universe should remain the same with time, so once again, it does not work.

The number of quasars drops off for very large redshifts (redshifts greater than about 50% of the speed of light). The Hubble Law says that these are for large look-back times. This observation is taken to mean that the universe was not old enough to produce quasars at those large redshifts. The universe did have a beginning.

The abundance of hydrogen, helium, deuterium, lithium agrees with that predicted by the Big Bang theory. The abundances are checked from the spectra of the the oldest stars and gas clouds which are made from unprocessed, primitive material. They have the predicted relative abundances.
Finding density of matter in the universe

\[
\text{density} = \frac{\text{local mass}}{\text{local volume}}
\]

Find \textit{density} of a representative volume of the universe.

Total mass = \textit{density} \times \text{total volume}.
**Faint gas shells around ellipticals**
Ellipticals have faint gas shells that need massive "dark" haloes to contain them. The gas particles are moving too quickly (they are too hot) for the gravity of the visible matter to hang onto it.

**Motion of galaxies in a cluster**
Galaxy cluster members are moving too fast to be gravitationally bound unless there is unseen mass.

**Hot gas in clusters**
The existence of HOT (i.e., fast moving) gas in galaxy clusters. To keep the gas bound to the cluster, there needs to be extra unseen mass.

**Quasar spectra**
Absorption lines from hydrogen in quasar spectra tells us that there is a lot of material between us and the quasars.

**Gravitational Lensing**
Gravitational lensing of the light from distant galaxies and quasars by closer galaxies or galaxy clusters enables us to calculate the amount of mass in the closer galaxy or galaxy cluster from the amount of bending of the light. The derived mass is greater than the amount of mass in the visible matter.

Current tallies of the total mass of the universe (visible and dark matter) indicate that all matter constitutes only 27% of the critical density.
The **Bullet Cluster.** This object appears to be two galaxy clusters that have merged.
Evidence for Dark Matter

The **Bullet Cluster.** This object appears to be two galaxy clusters that have merged. Most of the galaxies passed through each other, but the hot X-ray-emitting gas smashed into each other and stopped in its tracks.

The gravitational lensing analysis of background galaxies shows that all the mass (the dark matter) has followed the galaxies. The Dark Matter is acting solely as point sources that interact only by gravity. No other known model for gravity can explain this except Dark Matter.
The Bullet Cluster

Orange: stars
Red: X-ray gas
Blue: Mass from lensing measurements

See Clowe et al. 2006
The Bullet Cluster

See Clowe et al. 2006

Orange: stars  Red: X-ray gas  Blue: Mass from lensing measurements
The Bullet Cluster

Orange: stars
Red: X-ray gas
Blue: Mass from lensing measurements

See Clowe et al. 2006
The Bullet Cluster

Orange: stars
Red: X-ray gas
Blue: Mass from lensing measurements

See Clowe et al. 2006
The Bullet Cluster

Orange: stars
Red: X-ray gas
Blue: Mass from lensing measurements

See Clowe et al. 2006
Cosmology with the Cosmic Microwave Background

If the universe were perfectly homogeneous on all scales at the time of recombination ($z = 1000$), then the CMB should be perfectly isotropic over the sky.

Instead, it shows small-scale fluctuations (less than 1 part in $10^5$).
Deriving geometry of the universe from microwave background radiation
This is *directly* related to the CMB fluctuations!
CMB fluctuations are the direct probe of the Large Scale Structure

A large survey of distant galaxies shows the largest structures in the universe:

*Filaments and walls* of galaxy superclusters, and *voids*, basically empty space.
Deriving geometry of the universe from microwave background radiation

**GEOMETRY OF THE UNIVERSE**

**OPEN**
- Fluctuations largest on half-degree scale

**FLAT**
- Fluctuations largest on 1-degree scale

**CLOSED**
- Fluctuations largest on greater than 1-degree scale
The case of a missing Universe

CMB observations suggest that the universe is flat: $\Omega = 1$

Visible matter accounts for $\sim 4\%$ of the total mass-energy density: $\Omega_v = 0.04$

Dark matter accounts for only $27\%$ of the total mass-energy density: $\Omega_{\text{DM}} = 0.27$

The rest $70\%$ is something else!!

This something else is termed “dark energy”

It apparently causes the universe to accelerate in its expansion!!
Supernova Hubble Diagram

- An accelerating universe → given a red-shift, SN should be dimmer than anticipated
- The 1998 discovery by two independent groups
  Supernova Cosmological Project Saul Perlmutter et al.
  High-z Supernova Search Team Brian Schmidt et al.

SNe at $0.3 < z < 0.9$ were found to be, on the average, 25% less bright!
Supernovae are too faint
Model Universes on the $\Omega_{m,0} - \Omega_{\Lambda,0}$ plane
Redshift-Magnitude Relation using Supernovae Ia

News Flash

Adam Riess et al. (April 2001)

Detection of a SN-Ia at ultra-high \( z = 1.7 \) in the decelerating epoch

**SN 1997ff**  Serendipitously recorded by HST

\[
\frac{R(t^*)}{R(t_0)} = \frac{1}{(1+z)} \approx \frac{1}{3}, \quad \frac{t^*}{t_0} \approx \frac{1}{4}
\]

\( \approx 10 \text{ billion lightyears away} \) (by far the most distant SN ever detected)

Instead of dimming further, it's BRIGHTER by almost a factor of 2, compared to the expectation of continual dimming

*I.e.*, evidence for the bulge in the Hubble curve!
Time evolution of the universe

Accelerating now, but decelerating in the past
Now the age is right
Relativistic Cosmology

\[ \frac{d^2 R}{dt^2} = \left\{ -\frac{4}{3} \pi G \left[ \rho_m + \rho_{\text{rel}} + \frac{3(P_m + P_{\text{rel}})}{c} \right] + \frac{1}{3} \Lambda c^2 \right\} R \]

We can then define the mass density of the dark energy:

\[ \rho_{\Lambda} \equiv \frac{\Lambda c^2}{8\pi G} \]

And, we can define the pressure term due to dark energy:

\[ P_{\Lambda} = -\rho_{\Lambda} c^2 \]

Which lets us rewrite the acceleration equation as:

\[ \frac{d^2 R}{dt^2} = \left\{ -\frac{4}{3} \pi G \left[ \rho_m + \rho_{\text{rel}} + \rho_{\Lambda} + \frac{3(P_m + P_{\text{rel}} + P_{\Lambda})}{c} \right] \right\} R \]

It’s first integral:

\[ \left[ \left( \frac{1}{R} \frac{dR}{dt} \right)^2 - \frac{8}{3} \pi G (\rho_m + \rho_{\text{rel}}) - \frac{1}{3} \Lambda c^2 \right] R^2 = -kc^2 \]
Relativistic Cosmology

Look at the behavior of the scale factor to get the age of the Universe as a function of R (for flat geometry $k = 0$).

$$t = \sqrt{\frac{3}{8\pi G}} \int_0^R \frac{R' \, dR'}{\sqrt{\rho_{m,0} R' + \rho_{\text{rel},0} + \rho_\Lambda,0 R'^4}}$$

neglecting the contribution of relativistic particles during the first 55,000 yr ($\rho_{\text{rel}} = 0$) then we arrive at an expression:

$$t(R) = \frac{2}{3} H_0 \frac{1}{\sqrt{\Omega_\Lambda,0}} \ln \left[ \sqrt{\left( \frac{\Omega_\Lambda,0}{\Omega_m,0} \right) R^3} + \sqrt{1 + \left( \frac{\Omega_\Lambda,0}{\Omega_m,0} \right) R^3} \right]$$

Plugging in $R=1$ we get

$$t_0 = 4.32 \times 10^{17} \text{ s} = 1.37 \times 10^{10} \text{ yr}$$

And WMAP measured:

$$[t_0]_{\text{WMAP}} = 13.7 \pm 0.2 \text{ Gyr}$$
We can describe it with a metric (remember General Relativity?) The cosmological principle: Universe is isotropic (no special directions) and homogeneous (no spatial places). This leads to a special kind of metric (solution to Einstein's equations);

Friedmann, Lemaitre, Robertson, Walker (FLRW) metric

\[(ds)^2 = (c \, dt)^2 - R^2(t) \left[ \left( \frac{d\varpi}{\sqrt{1 - k\varpi^2}} \right)^2 + (\varpi \, d\theta)^2 + (\varpi \, \sin \theta \, d\phi)^2 \right] \]

where \(\varpi\) is the comoving coordinate which stays constant for a given object, and \(k \sim \frac{1}{R^2}\) is a constant describing the curvature.

Just like for Newtonian cosmology, \(k > 0\) universe is closed, \(k = 0\) universe is flat, \(k < 0\) universe is open.

For an observer at Earth \(\varpi = 0\).

\[d\mathcal{L} = \sqrt{-(ds)^2}\] is the differential proper distance for \(dt=0\).
**Cosmological redshift and time dilation**

\[ ds = 0 \text{ on the light ray} \]

**photon emitted at } \overline{\omega}_e \text{ observed at Earth } \overline{\omega} = 0 \]

\[
\frac{cdt}{R(t)} = \frac{d\omega}{\sqrt{1 - k\omega^2}} \quad \int_{t_e}^{t_0} \frac{cdt}{R(t)} = \int_{0}^{\overline{\omega}_e} \frac{d\omega}{\sqrt{1 - k\omega^2}}
\]

\[
\int_{t_e + \Delta t_e}^{t_0 + \Delta t_0} \frac{cdt}{R(t)} = \int_{0}^{\overline{\omega}_e} \frac{d\omega}{\sqrt{1 - k\omega^2}}
\]

subtract one integral from another:

\[
\Delta t_0 = \frac{\Delta t_e}{R(t_e)} = \Delta t_e (1 + z)
\]

\[
\frac{f_e}{f_0} = \frac{\lambda_0}{\lambda_e} = \frac{1}{R(t_e)} = 1 + z
\]
Cosmological Distances

Recall that proper distance is just the integral of metric, \([-\,(ds)]^{1/2}\). Along a radial line from the Earth to a distant object, \(d\theta=d\phi=0\), so:

\[
d_p(t) = R(t) \int_0^{\varpi} \frac{d\varpi'}{\sqrt{1-k\varpi'^2}} = R(t) \int_{t_e}^{t_0} \frac{c\,dt'}{R(t')}
\]

Note that \(d_{p,0} = d_p(t_0)\) is the proper distance, which is the distance to an object today. It is not the same as the distance between the Earth and the object when the photon was emitted.

The distance at other times is \(d_p(t) = R(t)\,d_{p,0}\).

\[
\begin{align*}
    d_{p,0} &= \varpi & \text{(for } k = 0) \\
    d_{p,0} &= \frac{1}{\sqrt{k}} \sin^{-1}(\varpi\sqrt{k}) & \text{(for } k > 0) \\
    d_{p,0} &= \frac{1}{\sqrt{|k|}} \sinh^{-1}(\varpi\sqrt{|k|}) & \text{(for } k < 0)
\end{align*}
\]

note: finite \(\varpi\)
Horizon distance

proper distance to the farthest observable point at time \( t \)

The distance to the horizon needs the expression of \( R(t) \)

\[
d_h(t) = \int_0^t \frac{cdt'}{R(t')}
\]

today:

\[
R(t) = \left( \frac{\Omega_{m,0}}{\Omega_{\Lambda,0}} \right)^{1/3} \sinh^{2/3} \left( \frac{3}{2} H_0 t \sqrt{\Omega_{\Lambda,0}} \right)
\]

Inserting this into our previous equation gives:

\[
d(t) = \left( \frac{\Omega_{m,0}}{\Omega_{\Lambda,0}} \right)^{1/3} \sinh^{2/3} \left( \frac{3}{2} H_0 t \sqrt{\Omega_{\Lambda,0}} \right) \times \int_0^t \frac{cdt'}{(\Omega_{m,0}/\Omega_{\Lambda,0})^{1/3} \sinh^{2/3} \left( \frac{3}{2} H_0 t' \sqrt{\Omega_{\Lambda,0}} \right)}
\]

Sadly, this must be solved numerically.... for our WMAP values we find that the distance from \( t=0 \) to \( t=t_0 \) is

\[
d_0 = 4.50 \times 10^{26} \text{ m} = 14,6000 \text{ Mpc} = 14.6 \text{ Gpc}
\]

This is the Horizon Distance.

\[
d_h(t) = 2ct \quad \text{radiation era}
\]

horizon expanded faster than the universe itself \( R(t) \).

\[
d_h(t) = 3ct \quad \text{matter-dominated era}
\]

But not in the future!
Cosmological Distances

Example: He-4 nuclei were formed when the temperature of the Universe was $10^9$ K at $t=178$ s. This early we can assume the Universe was mass+radiation dominated (no $\Lambda$) so the scale factor was $R(178s) = 2.73 \times 10^{-9}$. This sets the "horizon" distance at

$$d(t) = 2ct = 1.07 \times 10^{11} \text{ m} = 0.7 \text{ AU}.$$  

At this point the whole "visible" Universe would fit into the size of the Earth’s orbit.

The "visible" Universe is the "causally connected" Universe. At a time 178s only 0.7 AU regions were causally connected.

At a time $t=13.7$ Gyr later, this same 0.7 AU region has a present size of $d(t) / R(t) = 3.92 \times 10^{19} \text{ m} = 1.3 \text{ kpc}$.

We can currently see to 14.6 Gpc. The amount of the Universe that is causally connected today is much, much larger than it was at early times.
the maximum visible age of the source

even if the galaxy is visible today, its redshift will increase with time and eventually it will fade from view. The sky will become empty in the future! (except objects gravitationally bound to the Milky Way Galaxy)
### Table 3 from Wilkinson Microwave Anisotropy Probe (WMAP) Observations:
Preliminary Maps and Basic Results,
C. L. Bennett et al. (2003), accepted by the Astrophysical Journal;
available at http://lambda.gsfc.nasa.gov/

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<th>Symbol</th>
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<tr>
<td>CMB photon density (cm⁻³)</td>
<td>$n_\gamma$</td>
<td>410.4</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Baryon-to-photon ratio</td>
<td>$\eta$</td>
<td>$6.1 \times 10^{-10}$</td>
<td>$0.3 \times 10^{-10}$</td>
<td>$0.2 \times 10^{-10}$</td>
</tr>
<tr>
<td>Baryon-to-matter ratio</td>
<td>$\Omega_{b}\Omega_{m}^{-1}$</td>
<td>0.17</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Fluctuation amplitude in 8h⁻¹ Mpc spheres</td>
<td>$\sigma_8$</td>
<td>0.84</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Low-z cluster abundance scaling</td>
<td>$\sigma_8\Omega_m^{0.5}$</td>
<td>0.44</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Power spectrum normalization (at $k_0 = 0.05$ Mpc⁻¹)</td>
<td>$A$</td>
<td>0.833</td>
<td>0.086</td>
<td>0.083</td>
</tr>
<tr>
<td>Scalar spectral index (at $k_0 = 0.05$ Mpc⁻¹)</td>
<td>$n_s$</td>
<td>0.93</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Running index slope (at $k_0 = 0.05$ Mpc⁻¹)</td>
<td>$dn_s/d\ln k$</td>
<td>$-0.031$</td>
<td>0.016</td>
<td>0.018</td>
</tr>
<tr>
<td>Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc⁻¹)</td>
<td>$r$</td>
<td>$&lt;0.90$</td>
<td>95% CL</td>
<td>—</td>
</tr>
<tr>
<td>Redshift of decoupling</td>
<td>$z_{\text{dec}}$</td>
<td>1089</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Thickness of decoupling (FWHM)</td>
<td>$\Delta z_{\text{dec}}$</td>
<td>195</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Hubble constant</td>
<td>$h$</td>
<td>0.71</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Age of universe (Gyr)</td>
<td>$t_0$</td>
<td>13.7</td>
<td>0.2</td>
<td>0.2</td>
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<tr>
<td>Age at decoupling (kyr)</td>
<td>$t_{\text{dec}}$</td>
<td>379</td>
<td>8</td>
<td>7</td>
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<tr>
<td>Age at reionization (Myr, 95% CL)</td>
<td>$t_r$</td>
<td>180</td>
<td>220</td>
<td>80</td>
</tr>
<tr>
<td>Decoupling time interval (kyr)</td>
<td>$\Delta t_{\text{dec}}$</td>
<td>118</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Redshift of matter-energy equality</td>
<td>$z_{eq}$</td>
<td>3233</td>
<td>194</td>
<td>210</td>
</tr>
<tr>
<td>Reionization optical depth</td>
<td>$z_{\text{opt}}$</td>
<td>0.15</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Very Early Universe

Today $t_0$
- Life on earth
- Solar system
- Quasars

Galaxy formation
Epoch of gravitational collapse

Recombination
Relic radiation decouples (CBR)

Matter domination
Onset of gravitational instability

$t = 400,000$ years
$T = 3000 \text{ K} \ (1 \text{ eV})$

Nucleosynthesis
Light elements created - D, He, Li

$t = 3$ minutes
$T = 1 \text{ MeV}$

Quark-hadron transition
Hadrons form - protons & neutrons

$t = 10^{-6}$ seconds
$T = 1 \text{ GeV}$

Electroweak phase transition
Electromagnetic & weak nuclear forces become differentiated:
$SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1)$

$t = 10^{-11}$ seconds
$T = 10^3 \text{ GeV}$

The Particle Desert
Axions, supersymmetry?

Grand unification transition
$G \rightarrow H \rightarrow SU(3) \times SU(2) \times U(1)$
- Inflation, baryogenesis,
- monopoles, cosmic strings, etc.

$t = 10^{-35}$ seconds
$T = 10^{15} \text{ GeV}$

The Planck epoch
The quantum gravity barrier

$t = 10^{-43}$ seconds
$T = 10^{19} \text{ GeV}$
The unification of fundamental forces
Unification and Symmetry Breaking

At higher temperatures/energies, the relative strength of forces changes. This has been experimentally confirmed for the strong, E&M, and Weak forces.
Problems with the Big Bang

**Why is the cosmic background radiation so smooth?** The Universe is Homogeneous even though much of the Universe is not casually connected. This is the **Horizon Problem**.

**Why is the Universe so flat \((\Omega_0 \approx 1)\)?** The Universe is Homogeneous even though much of the Universe is not casually connected. This is the **Flatness problem**.

\[
\frac{1}{\Omega_0} - 1 = \left( \frac{1}{\Omega} - 1 \right) (1 + z)
\]

**Why are there no (or very, very few) magnetic monopoles?** These should be left over as topological defects from symmetry breaking. This is the **monopole problem**.

Fine tuning of all parameters is required to explain our present universe.
Do we live in a *special* universe??

- Change of physical constants by a very small amount would render impossible the life in the universe *as we know it*

- Adding or subtracting just one spatial dimension would make the formation of planets and atoms impossible

- Life as we know it needs a universe which is large enough, flat, homogeneous, and isotropic
Anthropic Principle

We observe the universe to be as it is because only in such a universe could observers like ourselves exist.

That is, selection effects would say that it is only in universes where the conditions are right for life (thus pre-selecting certain universe) is it possible for the questions of specialness to be posed.

This is sort of a solution, but can we do better?
Do we need a supernatural force?

How, and whether is it possible to cognize a real world?

Newton, Galileo, Kant, and many others:

*Faith and scientific reasoning should not interfere*
History of science teaches us that there is nothing special in the place we live

- Our local country is nothing special (ancient travelers)
- Planet Earth is nothing special (Copernicus)
- Milky Way galaxy is nothing special (Hubble)
- **Our part of the Universe is nothing special**
  - Inflation
  - Self-reproducing Universe
  - Eternal Big Bang and ensemble of universes

Guth, Linde, Vilenkin, Hawking, ...
**Problems with the Big Bang**

**Inflation:** theory that solves these problems. It was proposed in 1980s by Alan Guth and Andrey Linde. The basic concept is that when $t\approx 0$ (just after the big bang) the Universe was very small and everywhere was casually connected.

During inflation, the size of the Universe increased exponentially. This solves both the **Horizon** and **Flatness problems**.

In practice, there are many variants of inflation.
Virtual Particles

These are particles that spring into and out of existence without violating energy conservation. Quantum Mechanics and the uncertainty principle make this possible.

\[ \Delta E \Delta t \approx \hbar \]

You can create any amount of energy you want so long as it negates with \[ \Delta t < \frac{\hbar}{\Delta E} \].

Virtual particles are when a particle and its anti-particle appear at random with \[ m = \frac{\Delta E}{c^2} \] and then annihilate with \[ \Delta t < \frac{\hbar}{\Delta E} \].

This effect was experimental confirmed by Hendrick Casimir, who measured an attractive force between two uncharged parallel, conducting plates.

Virtual particles mean that the **Vacuum** is never a perfect Vacuum (there are always virtual particles present).
The False Vacuum and Inflation

At the end of the GUT epoch, $t \approx 10^{-36}$ s, when $T \approx 10^{28}$ K. The Universe was in a *false vacuum*. The universe was supercooled, which happens when the cooling rate is much faster than the phase-transition rate.

This is very similar to supercooled water, which can be supercooled to 20 K.

This false vacuum is like a phase transition. Physics works differently in different phases (consider gaseous, liquid, and solid $\text{H}_2\text{O}$).

When $t < 10^{-36}$ s, inflation likely began when quantum fluctuations governed by the Uncertainty Principle allowed a small region of space to enter a true vacuum state (at lower energy), where the rest of the Universe was in the false vacuum. The pressure within the true vacuum was zero, but it expanded exponentially into a Universe filled with negative pressure from the false vacuum.

During this time ($10^{-35}$ to $10^{-34}$ s) your book works out that Universe grew in size by a factor of $e^{100} = 3 \times 10^{43}$. 
So what if the dark energy is the energy density of the vacuum? Then why is it so small?
Landscape of the multiverse

Planck scale:

Planck Length
\[ \lambda_P \equiv \sqrt{\frac{G \hbar}{c^3}} = 1.6161 \times 10^{-33} \text{ cm} = 1.6161 \times 10^{-35} \text{ m.} \]

Planck Mass
\[ m_P \equiv \sqrt{\frac{\hbar c}{G}} = 2.17665 \times 10^{-5} \text{ g} = 2.17665 \times 10^{-8} \text{ kg.} \]

Planck density \(10^{94} \text{ g/cm}^3\)

Eternal multiverse;

Individual universes are being continuously “inflated” from a space-time “foam”.

Some of these universities can harbor life as we know it; others don’t.

A large fraction of universes CAN harbor life
The History of the Universe

- Afterglow Light Pattern: 380,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars: about 400 million yrs.
- Big Bang Expansion: 13.7 billion years

WMAP

[Diagram showing the timeline of the universe from the Big Bang to the development of galaxies.]
Fundamental Particles

Current Collider Physics experiments can reproduce the temperatures, energies and densities that prevailed back to when the Universe was $\sim 10^{-11}$ s.

<table>
<thead>
<tr>
<th>Era or Event</th>
<th>Time</th>
<th>Temperature (kT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck Era</td>
<td>$&lt; 5 \times 10^{-44}$ s</td>
<td>$&gt; 10^{19}$ GeV</td>
</tr>
<tr>
<td>Planck Transition</td>
<td>$5 \times 10^{-44}$ s</td>
<td>$10^{19}$ GeV</td>
</tr>
<tr>
<td>Grand Unification Era</td>
<td>$5 \times 10^{-44}$ s to $10^{-36}$ s</td>
<td>$10^{19}$ GeV to $10^{15}$ GeV</td>
</tr>
<tr>
<td>Inflation</td>
<td>$10^{-36}$ s to $10^{-34}$ s</td>
<td>$10^{15}$ GeV</td>
</tr>
<tr>
<td>Electroweak Era</td>
<td>$10^{-34}$ s to $10^{-11}$ s</td>
<td>$10^{15}$ GeV to 100 GeV</td>
</tr>
<tr>
<td>Electroweak Transition</td>
<td>$10^{-11}$ s</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Quark Era</td>
<td>$10^{-11}$ s to $10^{-5}$ s</td>
<td>100 GeV to 200 MeV</td>
</tr>
<tr>
<td>Quark-Hadron Transition</td>
<td>$10^{-5}$ s</td>
<td>200 MeV</td>
</tr>
<tr>
<td>Neutrino Decoupling</td>
<td>0.1 s</td>
<td>3 MeV</td>
</tr>
<tr>
<td>Electron-Positron annihilation</td>
<td>1.3 s</td>
<td>1 MeV</td>
</tr>
</tbody>
</table>