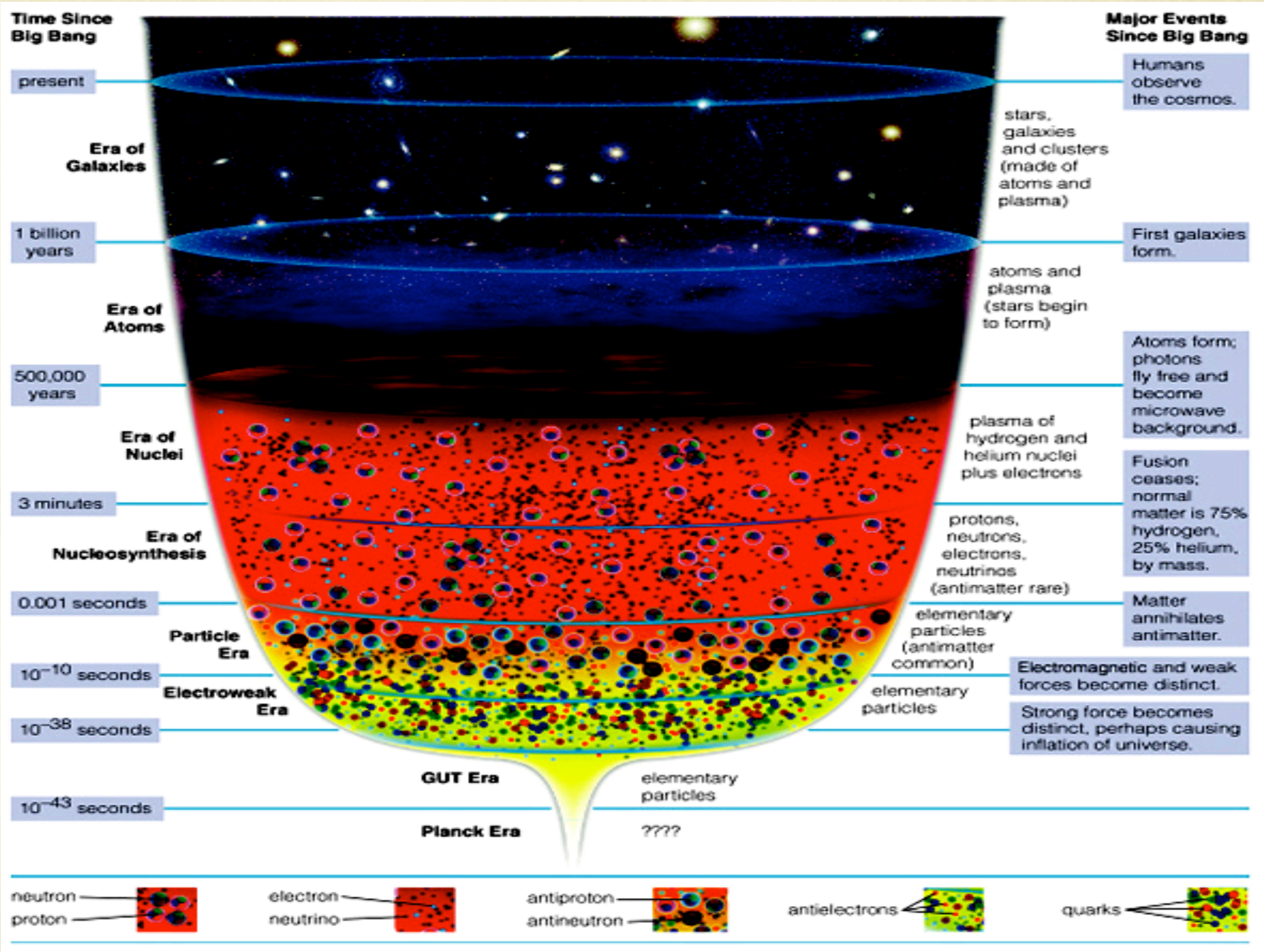
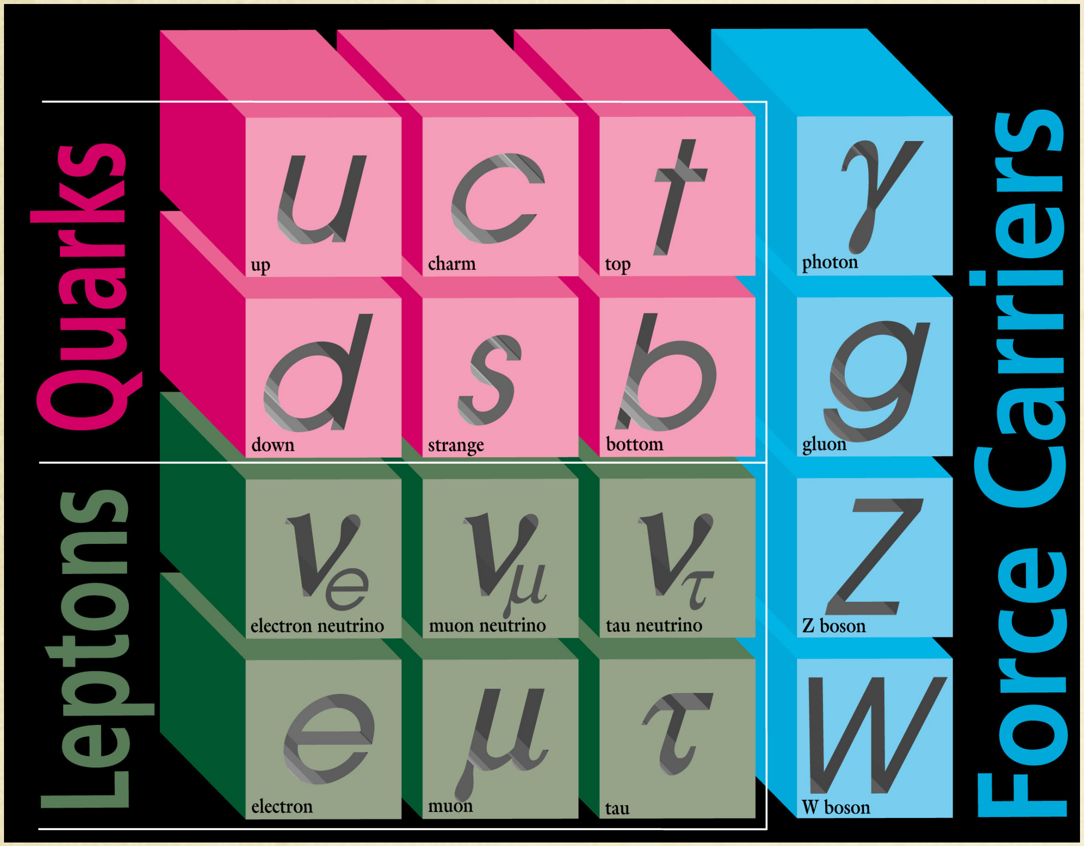
The Early Universe:
Primordial Nucleo-synthesis and Cosmic Microwave Background



The Standard Model



<u>The SM states that:</u>

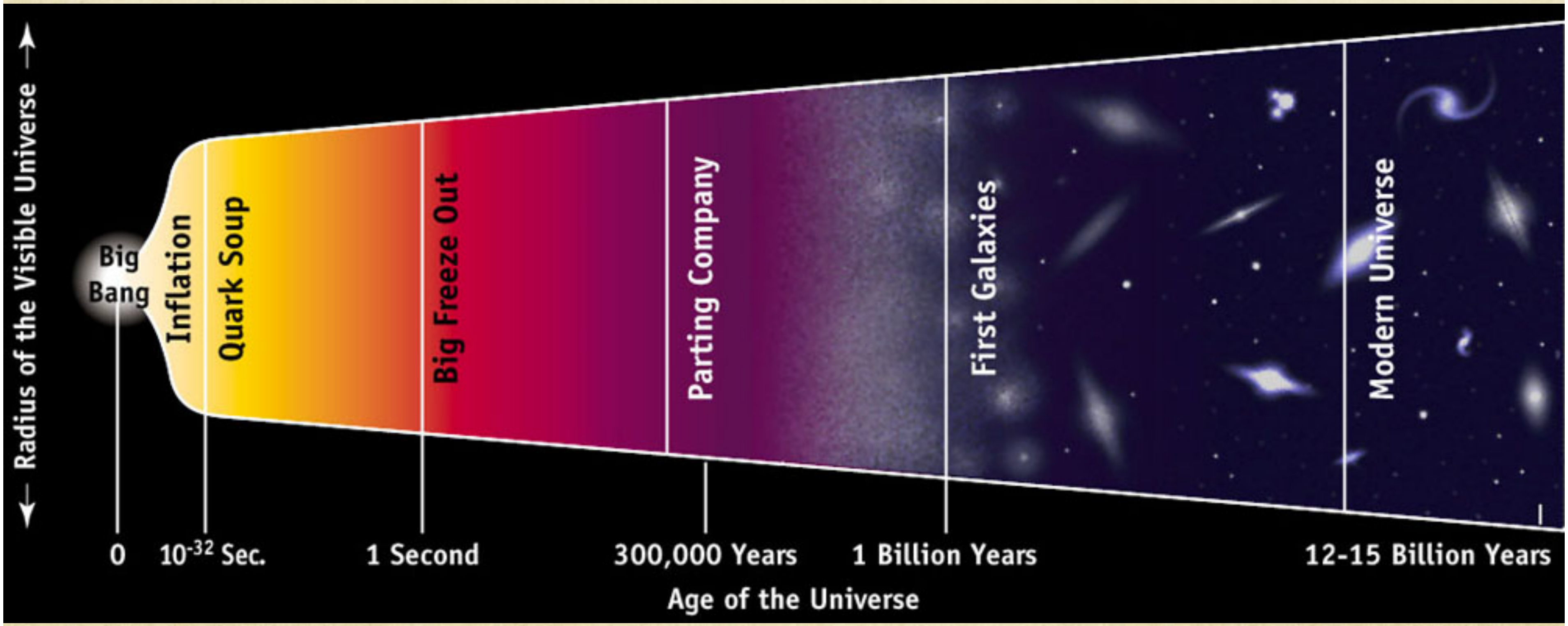
The world is made up of *quarks* and *leptons* that interact by exchanging *bosons*.

A *Higgs* field interacts as well, giving particles their masses.

Lepton Masses: $Me<M\mu<M\tau$; $M\nu\sim0$.*

Quark Masses: $Mu \sim Md < Ms < Mc < Mb \ll Mt$

Timeline: the Cosmic Thermal History



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

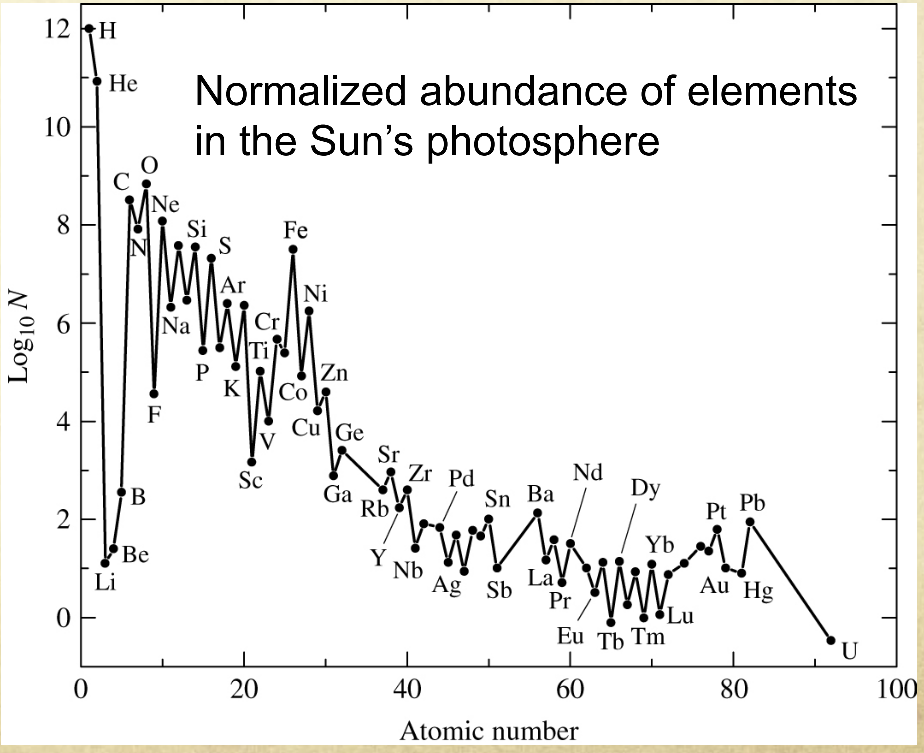
Hot Big Bang

From this evolution of temperature we can thus reconstruct the detailed

Cosmic Thermal History

The Idea of a Big Bang

- George Gamow and Ralph Alpher proposed in 1948 the idea of an initial hot dense Universe to explain the abundance of elements
- Fred Hoyle, the proponent of a steady-state Universe, referred to their work publicly as a *Big Bang idea*
- The mean free path of photons in a hot and dense universe would have been short so that the Universe would have been in a thermodynamic equilibrium (besides expansion)
- The blackbody spectrum describes the radiation in such an environment



Cosmic Background Radiation

- George Gamow and Ralph Alpher calculated a value of 5 K for the remainder of the radiation in the present day Universe
- It turns out that the present blackbody temperature T_0 and the primordial temperature are related

$$R\,T = T_0$$

- The fusion of hydrogen atoms requires $T \approx 10^9$ K and $\rho \approx 10^{-2}$ kg m^{-3}
- Combining with our earlier results

$$R^3(t)\,\rho(t) = \rho_0$$

and $\rho_{b0} = 4.17 \cdot 10^{-28}$ kg m^{-3}

yields for the scale factor

$$R = (\rho_{b0} / \rho_b)^{1/3} = 3.47 \cdot 10^{-9}$$

- This results to

$$T_0 = R\;T(R) = 3.47\ \mathrm{K}$$

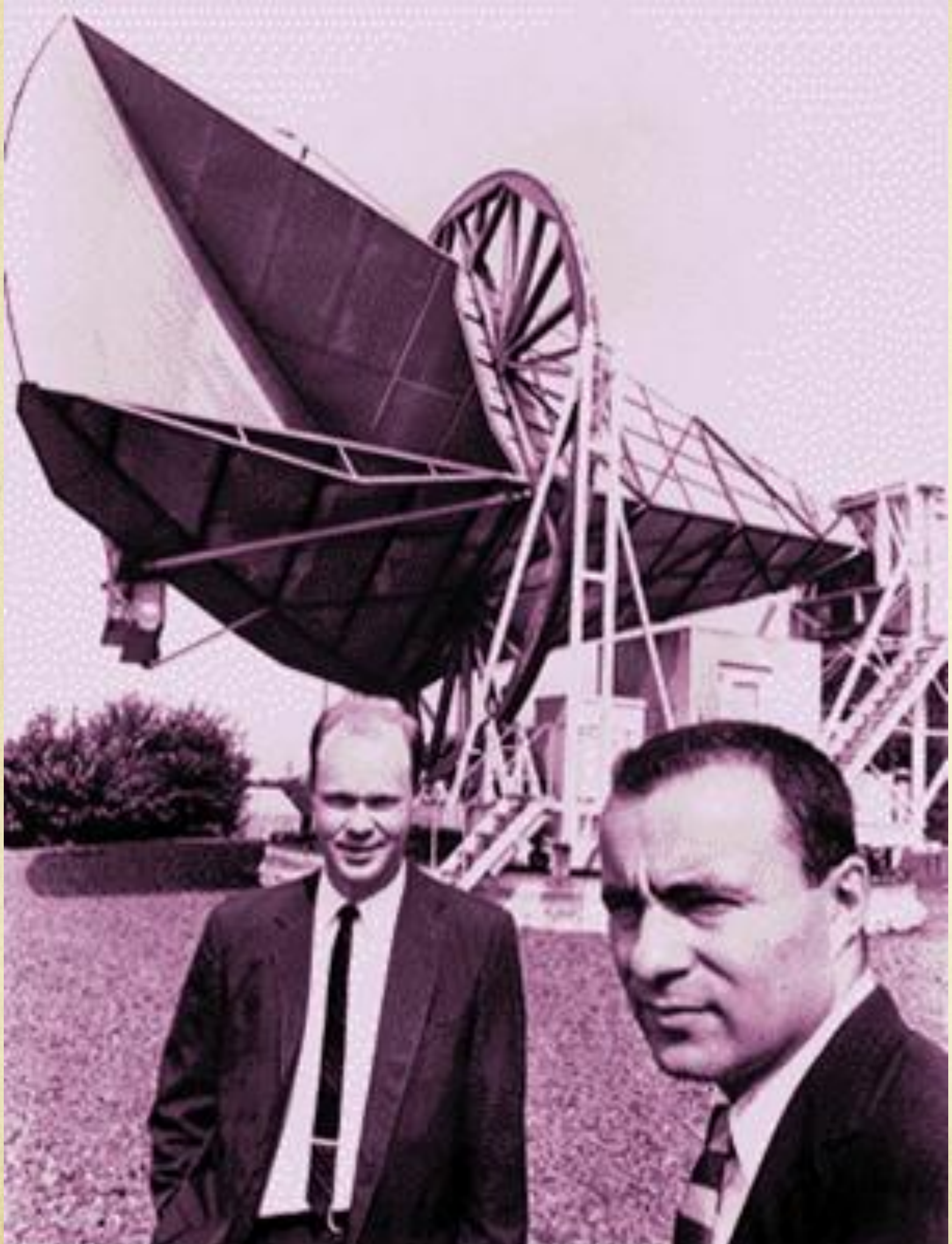
Cosmic Microwave Background

- Using Wien's Law, we can obtain the peak wavelength of the blackbody spectrum

$$\lambda_{max} = \frac{0.00290 \text{ m K}}{T_0} = 8.36 \cdot 10^{-4} \text{ m}$$

- In 1965 Arno Penzias and Robert Wilson detected a background radio signal when using a horn antenna for communication with the Telstar satellite
- Their background radiation corresponded to a 2.7 K blackbody with a peak wavelength of $\lambda_{max} \approx 1.06$ mm
- The present day value for the Cosmic Microwave Background (CMB) from the WMAP satellite measurements is

$$T_0 = 2.725 \pm 0.002 \text{ K}$$

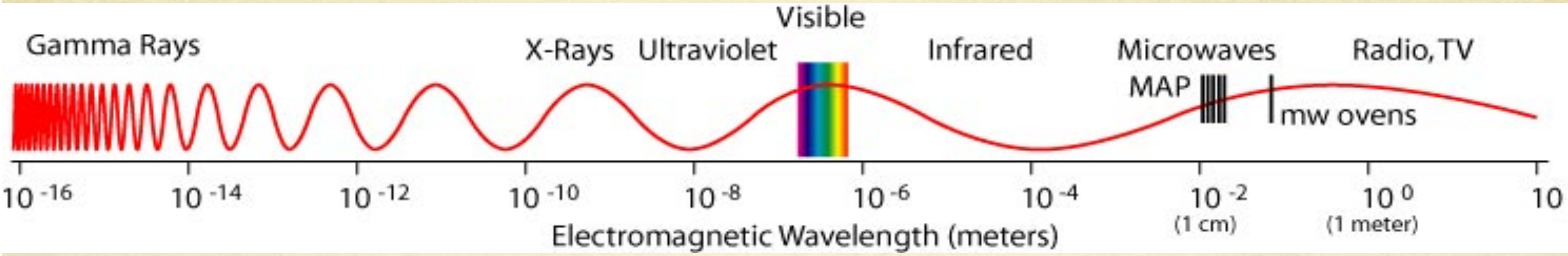


Discovered by Arno Penzias and Robert Wilson in 1960-65 while employed by AT&T's Bell Labs and attempting to find the source of noise in an antenna used to bounce telephone signals off metallic balloons high in the atmosphere.

They won the Nobel prize in 1978.

CMB spectrum

red-shift

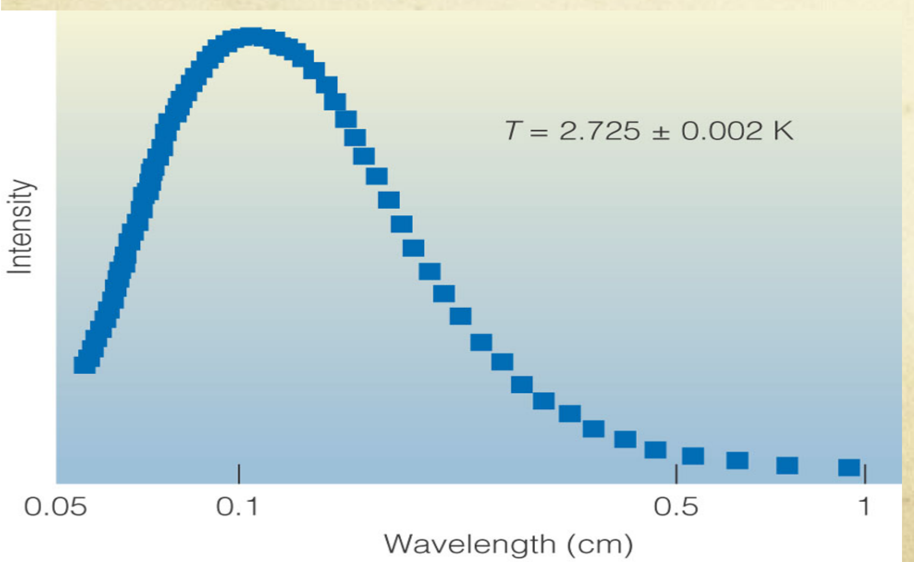


3000 K Blackbody (Optical)

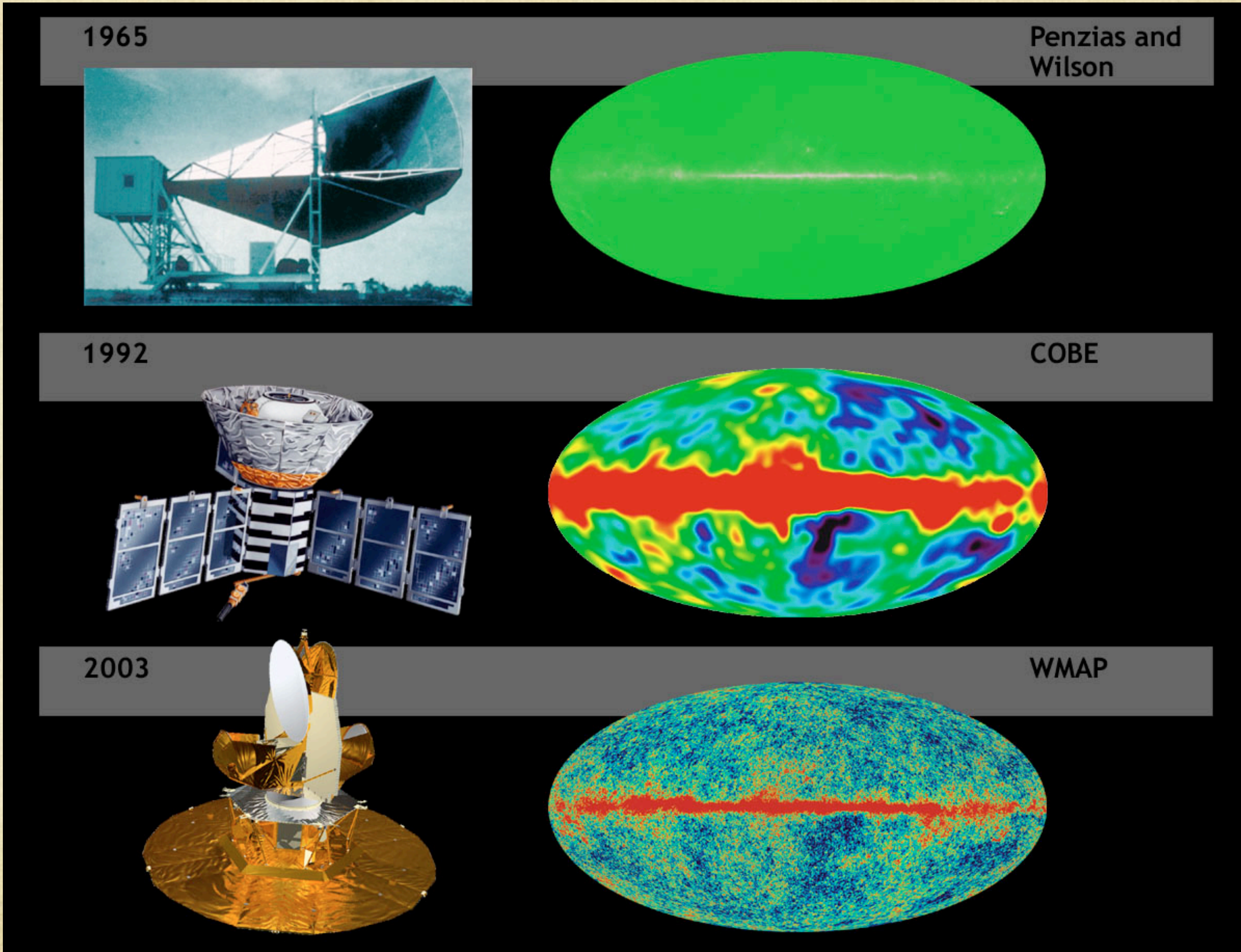
red-shift z ~ 1000

keeps spectrum shape

2.73 K Blackbody (microwaves)



- Accurate black-body shape
- T = 2.725 ± 0.002 K
- Early Universe was hot


1965
Penzias and Wilson
1992
COBE
2003
WMAP

Cosmic Microwave Background

- The Cosmic Microwave Background originates from the Big Bang when the Universe was a singularity
- We expect that the radiation is isotropic and that any observer measures the same spectrum
- A Doppler shift emerges from the observer's peculiar velocity v relative to the *Hubble flow*
- This shift in wavelength can be expressed as a change of temperature

$$T_{\mathrm{moving}} = T_{\mathrm{rest}} \frac{(1 - \beta^2)^{1/2}}{1 - \beta \cos\theta}$$

$$\approx T_{\mathrm{rest}} (1 + \beta \cos\theta)$$

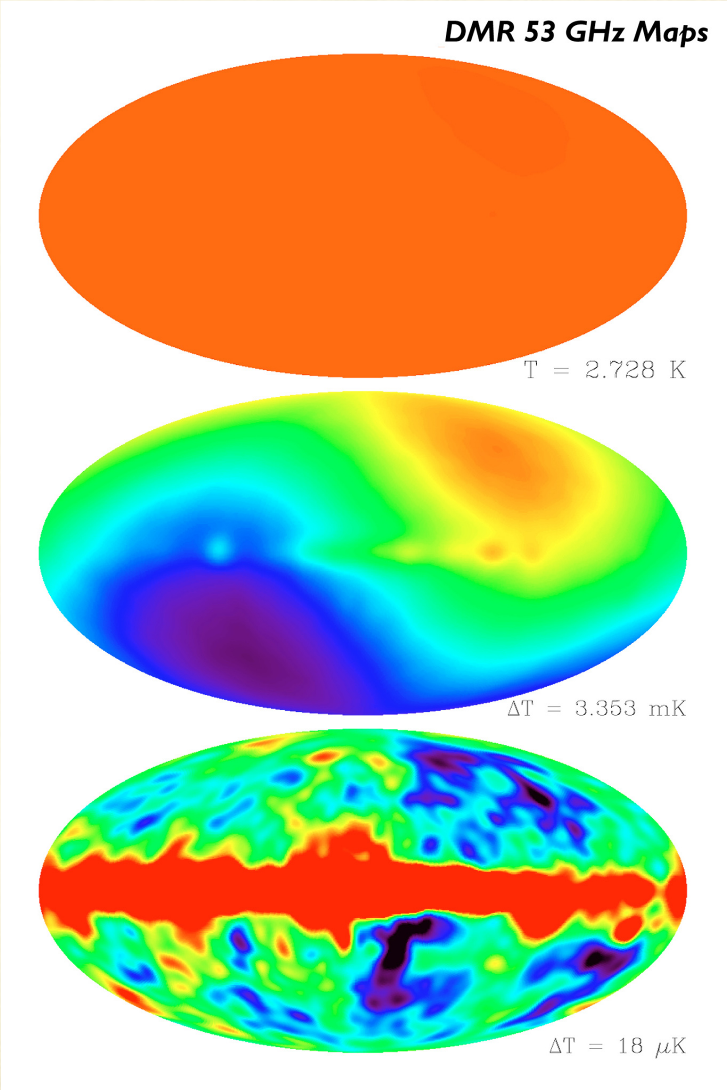
- The second term on the rhs is called the *dipole anisotropy* of the CMB

$\beta = v / c$

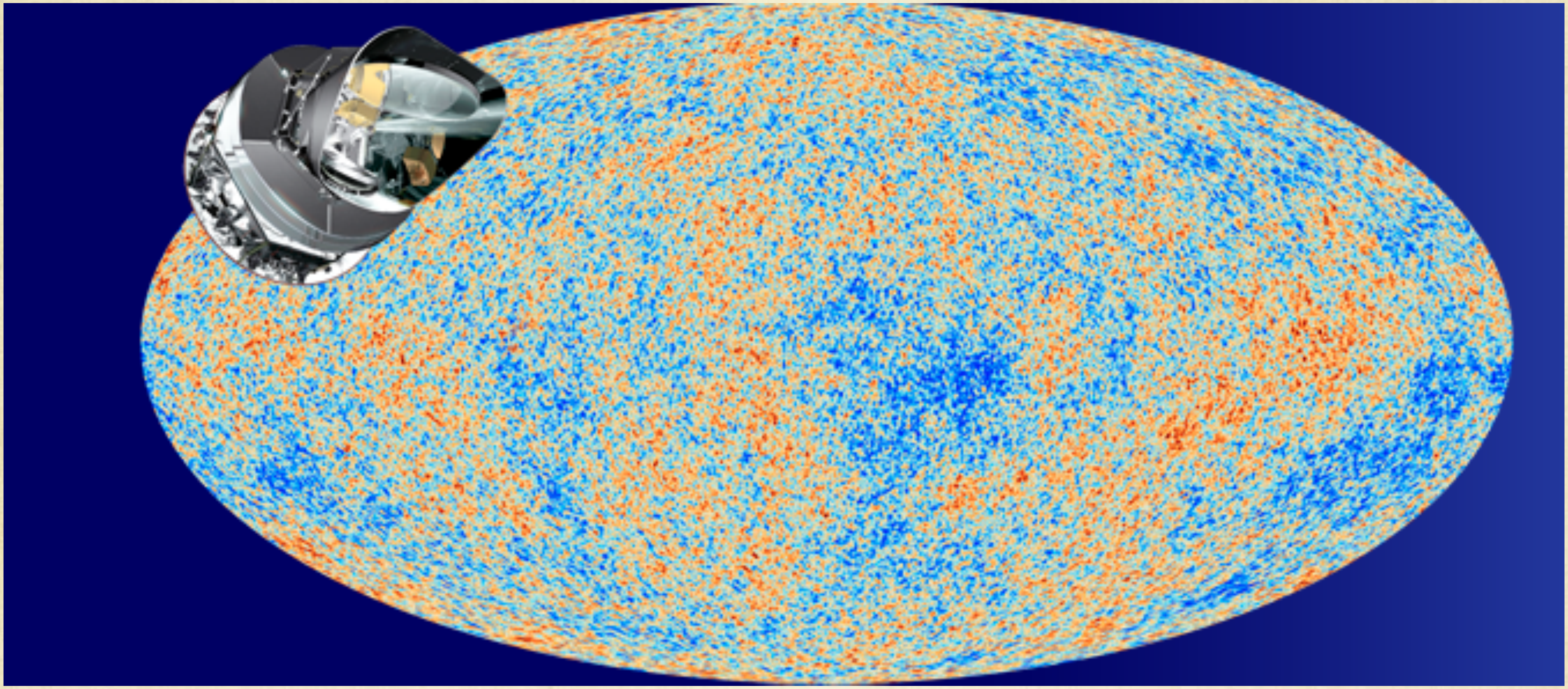
Dipolar Anisotropy and Resolution

Temperature resolution dependence from COBE data

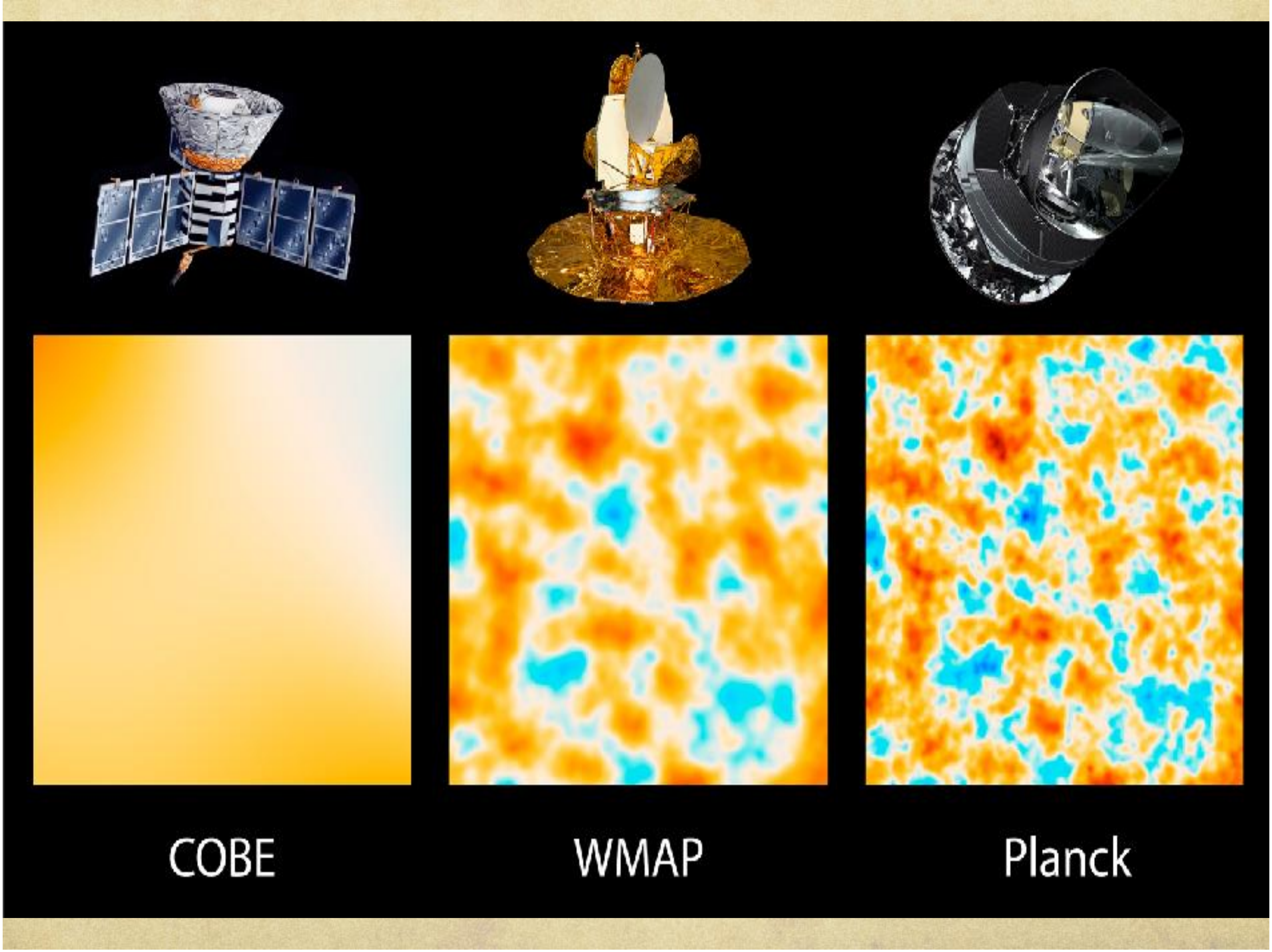
- At around 2.73 K the microwave sky looks very homogeneous
- At a resolution of 3 mK the dipolar anisotropy due to the motion of the Earth towards the center of the local galaxy cluster with respect to the Hubble flow becomes apparent
- After subtracting the dipolar anisotropy, the inhomogeneity of the microwave structure is visible at a resolution of $2 \cdot 10^{-5}$ K



The Planck Mission



The newly estimated Hubble's constant, is 67.15 +/- 1.2 km/sec/Mpc
This is less than prior estimates derived from space telescopes, such as NASA's Spitzer and Hubble, using a different technique. The new estimate of dark matter content in the universe is 26.8 %, up from 24 %, while dark energy falls to 68.3 %, down from 71.4 %. Normal matter now is 4.9 %, up from 4.6 %.


COBE
WMAP
Planck

Brief History of Time

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

(I)

fundamental physics:

- totally unknown

$t < 10^{-43}$ sec

Planck Era

Origin universe

???

History of the Universe in Four Episodes: II.

(II)

fundamental physics:

- poorly known
- speculative

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

VERY early universe

curvature/ flatness

- `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)

$t > 10^{13}$ sec

Post (Re)Combination universe

complex macrophysics:

-Fundamentals known

- complex interplay

- structure formation:

stars,
galaxies
clusters
…

Products

Episode's 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 $< t <$ 3min
Radiation Era	radiation-matter equivalence recombination & decoupling	3 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

Lepton Era

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

130 > T > 0.5MeV 10^{12} K > T > 5×10^{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	$T \sim 10^{12}$ K
◊	Neutrino Decoupling	$T \sim 10^{10.5}$ K; $z \sim 10^{10}$
◊	Electron-Positron Annihilation	$T \sim 10^{9}$ K; $z \sim 10^{9}$, $t \sim 1$ min
◊	Primordial Nucleosynthesis	$T \sim 10^{9}$ K; $t \sim 200$ sec (3 min)

Neutrino Decoupling

- Weak interactions, e.g. $$e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$$

  get so slow that neutrinos decouple from the e^+, e^- plasma. Subsequently, they proceed as a relativistic gas with its own temperature T.
- Because they decouple before the electron-positron annihilation, they keep a temperature T which is lower than the photon temperature (which gets boost from released annihilation energy):

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

- The redshift of neutrino decoupling, $z \sim 10^{10}$, defines a surface of last neutrino scattering, resulting in a "Cosmic Neutrino Background" with present-day temperature $T \sim 1.95$ K.

Electron-Positron Annihilation

$T \sim 10^9$ 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^-, photon plasma, the photons acquire a temperature $T >$ neutrino temperature .

Electron-Positron Annihilation

T $\sim 10^9$

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 ~1089, the epoch of recombination.
- Within 2 months after the fact, thermal equilibrium of photons is restored by a few scattering processes:
- ● Compton scattering

  ● double Compton scattering

  ● free-free scattering

The net result is the perfect blackbody CMB spectrum we observe now

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

<u>Freeze-out of Neutron-Proton ratio</u>: $$\boxed{\frac{N_n}{N_p} \approx \frac{1}{6}}$$

Primordial Nucleosynthesis

- Protons and neutrons were transformed into one-another via

$$n \rightleftharpoons p^+ + e^- + \nu_e$$

$$n + e^+ \rightleftharpoons p^+ + \overline{\nu}_e$$

$$p^+ + e^- \rightleftharpoons n + \nu_e$$

- The energy difference between proton and neutron is 1.293 MeV, while the thermal energy of the nucleons at 10^{12} K is 86 MeV
- The equilibrium number density ratio for protons and neutrons is given by the Boltzmann distribution

$$\frac{n_n}{n_p} = e^{-(m_p - m_n)c^2/(kT)} = 0.985$$

For $T = 10^{12}$ K

Primordial Nucleosynthesis

- As the Universe cooled, the neutron-proton conversion processes maintained the equilibrium
- When the temperature reached about 10^{10} K, these reaction rates decreased
  - The expansion had reduced the energy of the neutrinos to the point that they could not participate in the conversion reactions
  - The characteristic thermal energy of the photons, kT, fell below 1.022 MeV needed for the pair-production process leading to a small remainder of excess electrons
- As a result, not enough neutrons could be produced to balance the number of protons and the number density ratio was frozen at

$$\frac{n_n}{n_p} = e^{-(m_p - m_n)c^2/(kT)} = 0.223$$

For $T = 10^{10}$ K

Primordial Nucleosynthesis

- The time to cool from 10^{10} K to 10^{9} K took about 176 s during which neutrons decayed into protons with a half life of 614 s
- This resulted into a number density of

$$\frac{n_n}{n_p} = 0.176$$

- Below 10^{9} K neutrons and protons fused readily into deuterons and higher nuclei, tritium and helium
- Almost all neutrons were fused into helium-4, leaving only traces of the other nuclei
- Given the proton-neutron number density ratio of 0.176 yields a helium-4 to total nucleon ratio of 0.299
- This is close to the observed primordial relative abundance of helium-4 between 23% and 24%

Primordial Nucleosynthesis

- Note that from the ratio $N_n/N_p \sim 1/6$ 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 …

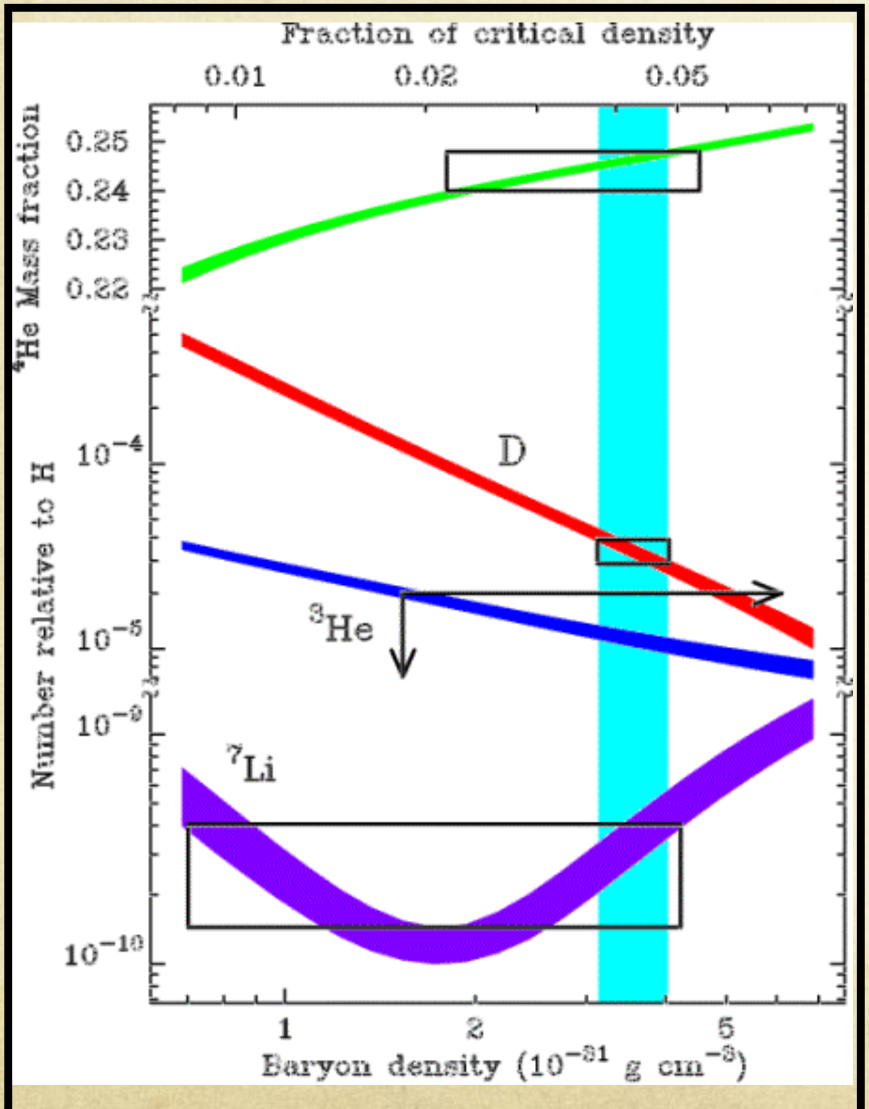
After freeze-out of protons and neutrons, a number of light element nucleons forms through a number of nuclear reactions involving the absorption of neutrons and protons:

- Deuterium
- ^{3}He
- ^{4}He

$$\begin{aligned} n + p &\rightleftharpoons \mathrm{D} + \gamma \\ \mathrm{D} + p &\rightleftharpoons {}^3\mathrm{He} \\ {}^3\mathrm{He} + n &\rightleftharpoons {}^4\mathrm{He} \end{aligned}$$

- 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 are too low for any significant synthesis.
- 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:

$$0.005 \lesssim \Omega_b h^2 \lesssim 0.026$$

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

$$\begin{aligned} \Omega_b h^2 &\approx 0.0224 \pm 0.0009 \\ \Omega_b &\approx 0.044 \pm 0.004 \end{aligned}$$

- Not that these nuclear reactions also occur in the Sun, but at a considerably lower temperature: T ~ 1.6×10^7 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:

$$\begin{aligned} \rho_{\odot,centre} &\approx 10^2 \quad \mathrm{g\,cm^{-3}} \\ \rho_{univ,t=3min} &\approx 10^{-8} \; \mathrm{g\,cm^{-3}} \end{aligned}$$

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..

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 $z \sim 2 \times 10^4$

(equivalence matter-radiation)

◊ Recombination & Decoupling $z \sim 1089$; $t \sim 3\ 79{,}000$ yrs

Radiation-Matter Equality

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

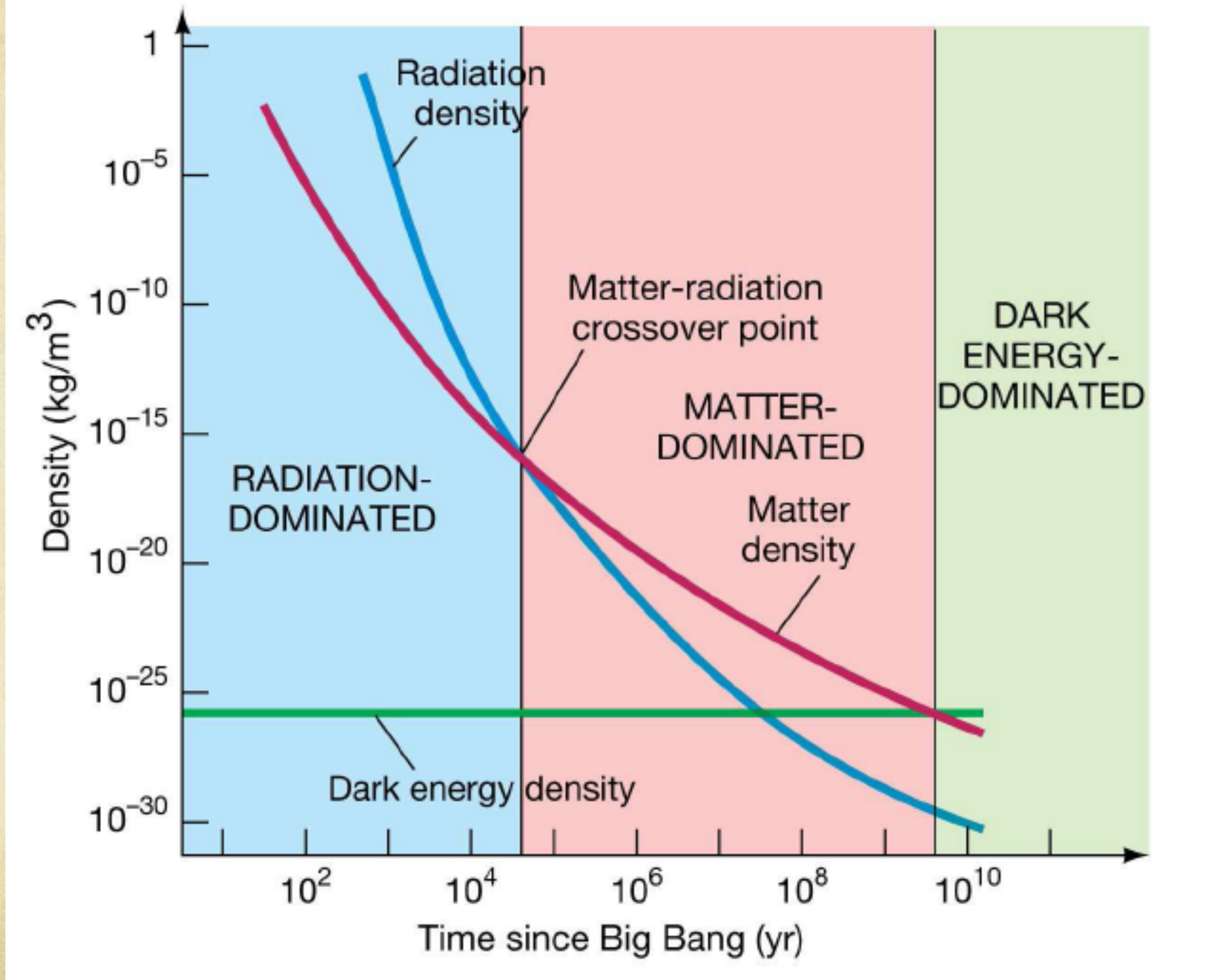
$$1 + z_{eq} = 4.0 \times 10^4 \; \Omega_m h^2$$

- 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.



Radiation density
Matter-radiation crossover point
DARK ENERGY-DOMINATED
MATTER-DOMINATED
RADIATION-DOMINATED
Matter density
Dark energy density
Density (kg/m³)
1
10⁻⁵
10⁻¹⁰
10⁻¹⁵
10⁻²⁰
10⁻²⁵
10⁻³⁰
10²
10⁴
10⁶
10⁸
10¹⁰
Time since Big Bang (yr)

Recombination Epoch

T ~ 3000 K

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

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

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

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. Thermodynamically it becomes favorable to form neutral (hydrogen) atoms H (because the photons can no longer destroy the atoms):

$$p + e^- \rightleftharpoons \mathrm{H}$$

- 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 379,000 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:

•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 our telescopes ...

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:

$$p = n k T$$

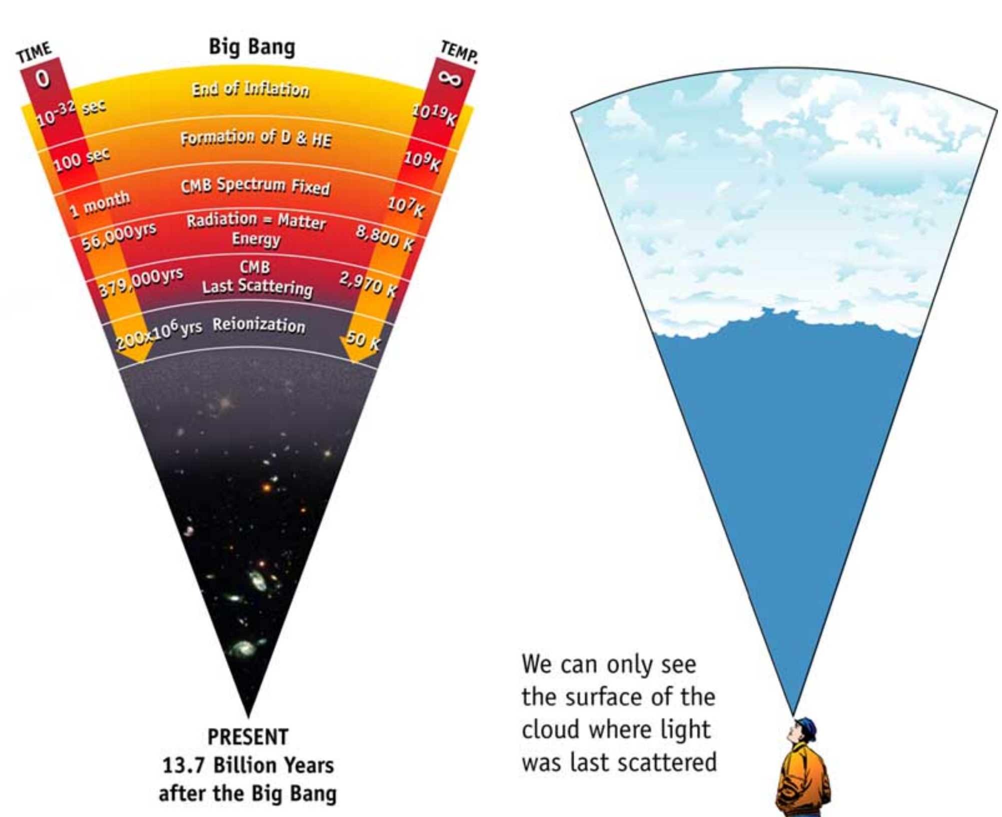
Recombination Epoch

- 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.