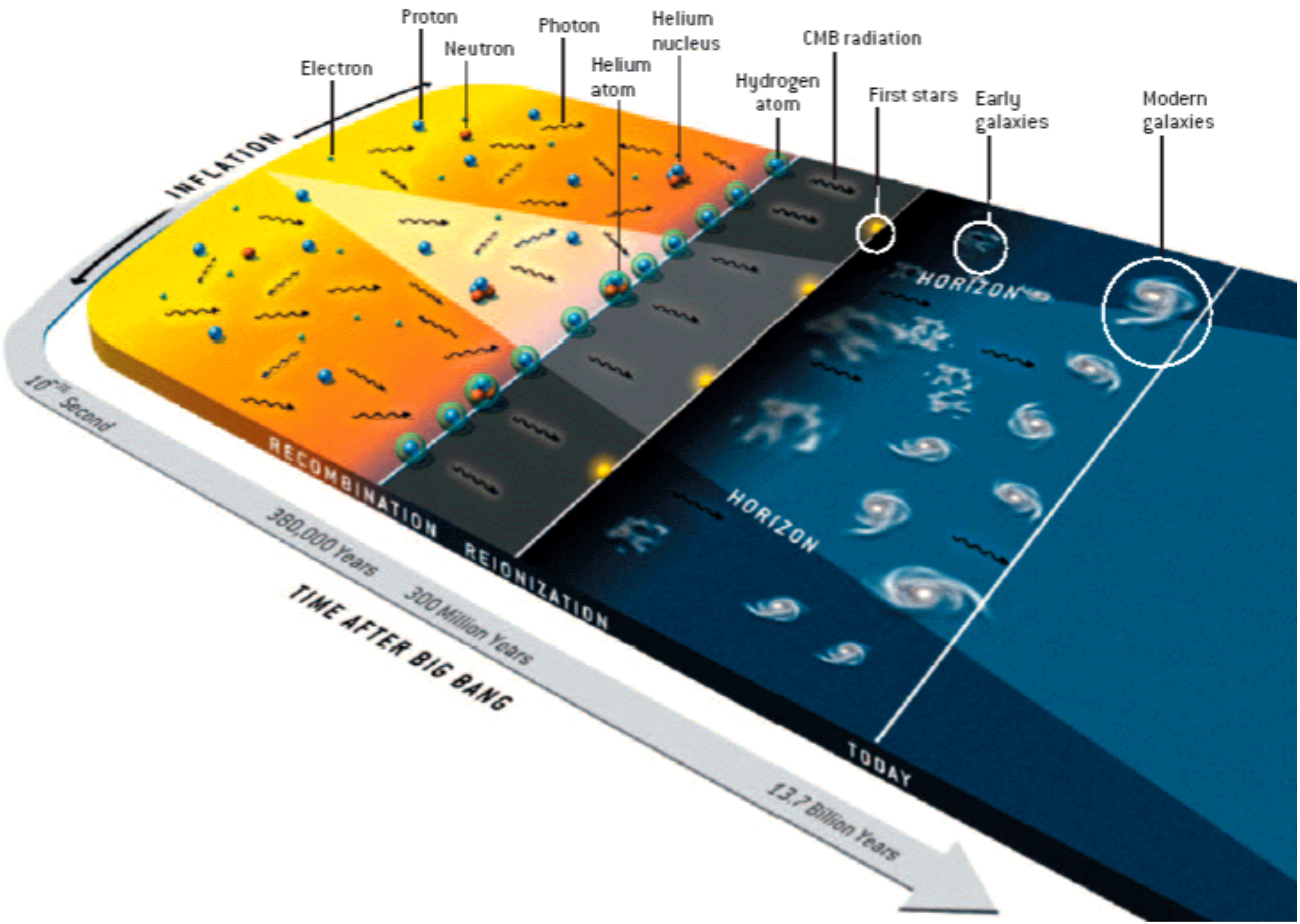
The Early Universe

The Key Ideas

- Pushing backward in time towards the Big Bang, the universe was hotter and denser in a fairly predictable manner (aside from surprising "glitches" such as the inflation…)
- At any given time, the temperature translates into a characteristic mass of particles, which dominate that epoch: the Universe as the ultimate accelerator?
- As the energies increase, different physical regimes and different fundamental interactions come into play
- The closer we get to the Big Bang (i.e., further away from the experimentally probed regime), the less certain the physics: the early Universe as the laboratory of physics beyond the standard model?
- Our extrapolations must break down by the epoch of $\sim 10^{-43}$ sec $\sim$ Plack time, where quantum gravity must be important



Proton
Neutron
Electron
Photon
Helium atom
Helium nucleus
Hydrogen atom
CMB radiation
First stars
Early galaxies
Modern galaxies
INFLATION
HORIZON
HORIZON
RECOMBINATION
REIONIZATION
TODAY
10^{-36} Second
380,000 Years
300 Million Years
13.7 Billion Years
TIME AFTER BIG BANG

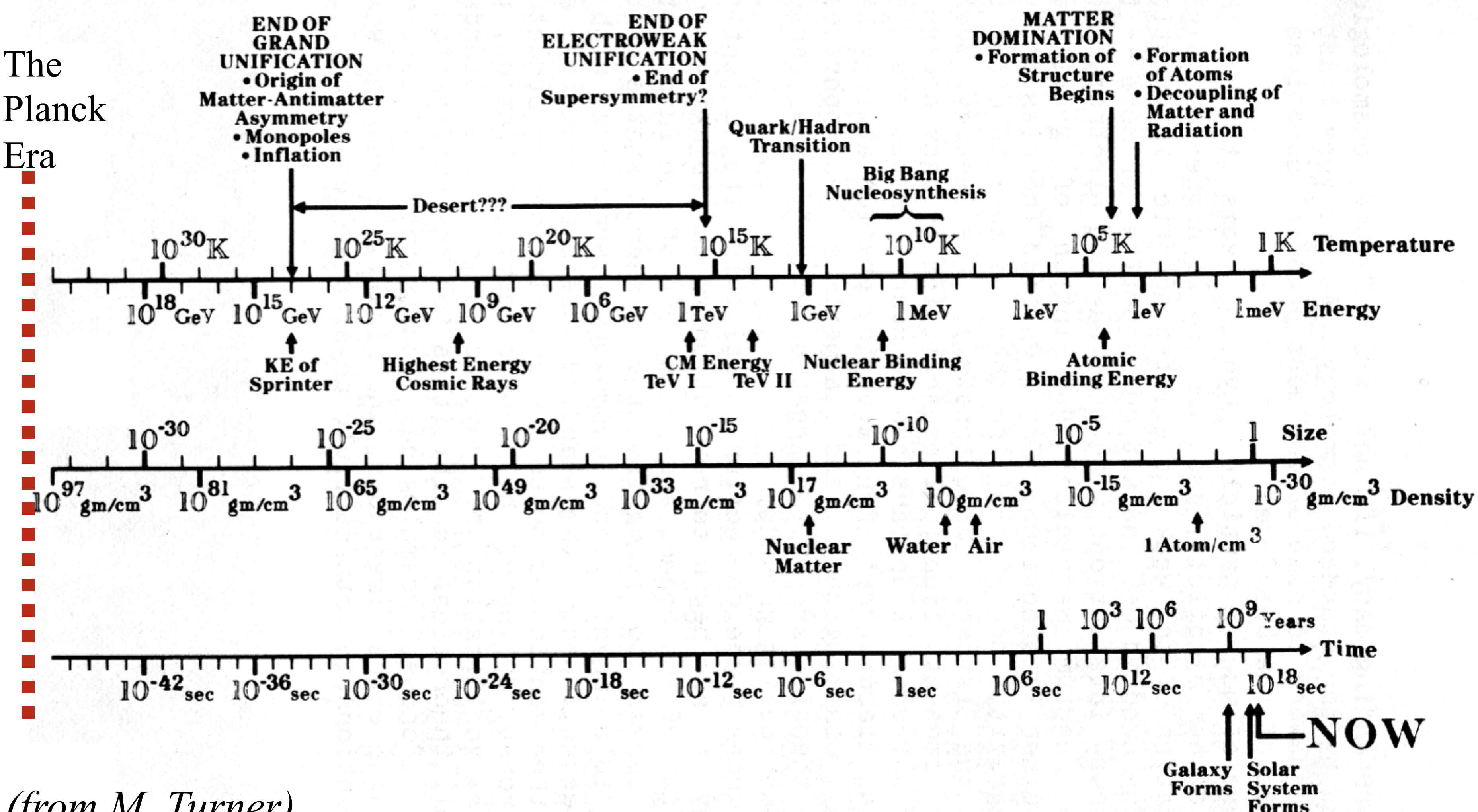
Some Key Moments in the Thermal History of the Universe:

- **Planck era, t ~ 10^{-43} sec**: quantum gravity, … ??? …
- **Inflation, t ~ 10^{-33} sec**: vacuum phase transition, exponential expansion
- **Grand Unification, t ~ 10^{-32} sec**: strong and electroweak interactions split
- **Baryogenesis , t ~ 10^{-6} sec**: quark-hadron transition
- **Nucleosynthesis , t ~ 1 ms to 3 min**: D, He, Li, Be form
- **Radiation to matter dominance transition, t ~ 10^{5} yr**: structure begins to form
- **Recombination, t ~ 380,000 yr**: hydrogen becomes neutral, CMBR released, dark ages begin
- **Reionization, t ~ 0.3 - 1 Gyr**: first galaxies and QSOs reionize the universe, the cosmic renaissance

The Cosmic Thermal History

… on a logarithmic time axis - a theorist’s delight!

The Planck Era

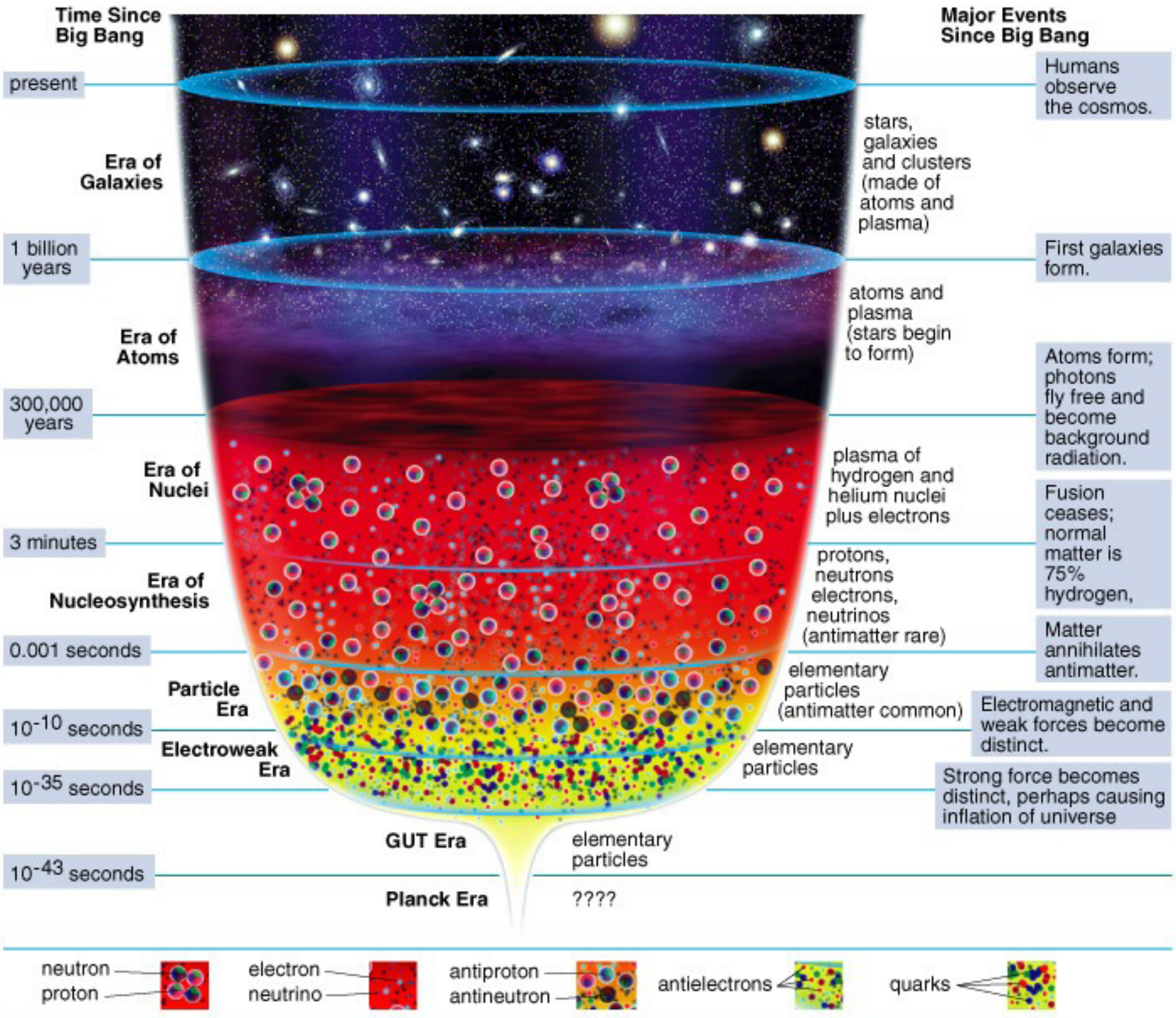


(from M. Turner)

Thermal History of the Early Universe

Age	Temperature	Processes
$t < 10^{-10}$ s	$T > 10^{15}$ K	GUT
$10^{-10} < t < 10^{-4}$ s	$10^{15} > T > 10^{12}$ K	e^+, e^-,quarks,γ,ν
$t \sim 10^{-4}$ s	$T \sim 10^{12}$ K	Quarks-> n, p $\mu^+\mu^- > \nu_\mu,\nu_\mu$
$10^{-10} < t < 10^{-4}$ s	$10^{12} > T > 10^{10}$ K	e^+, e^-, n, p, γ,ν_e
$t \sim 0.01$ s	$T \sim 10^{11}$ K	assymetry in n, p
$t \sim 4$ s	$T \sim 5 \times 10^{9}$ K	e^+, $e^- \rightarrow \nu_e,\nu_e$ $n \rightarrow p + e^- + \nu_e$
$t \sim 100$ s	$T \sim 10^{4}$ K	nucleosynthesis
$t \sim 10^{11}$ s	$T \sim 16\,500$ K	Matter domination
$t \sim 10^{13}$ s	$T \sim 3000$ K	Decoupling

Another Schematic Outline:



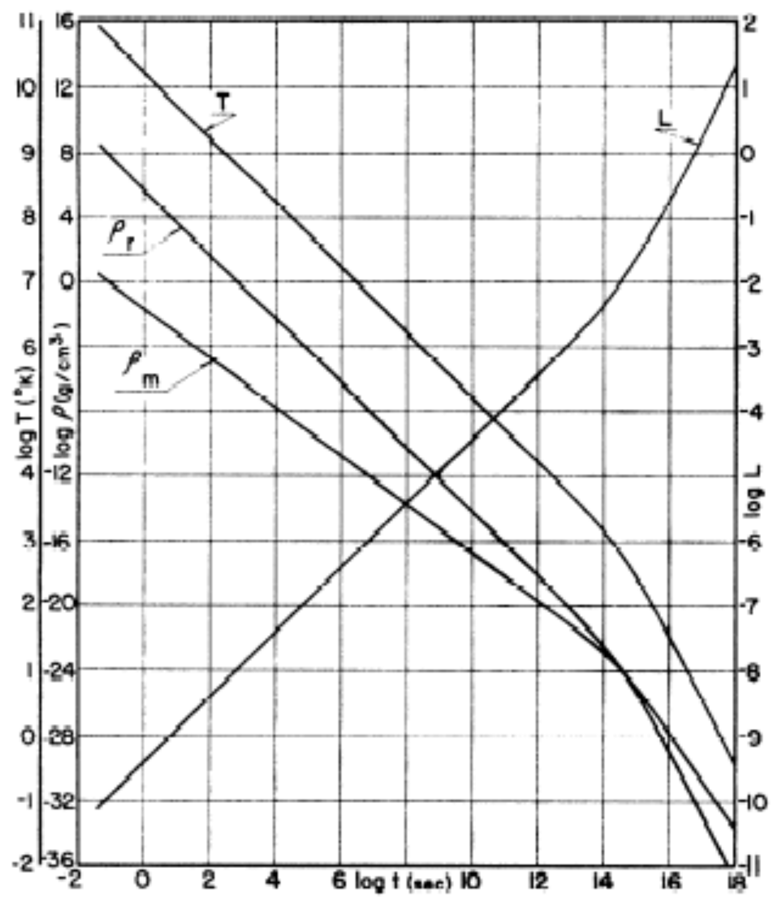
Empirical Evidence

- **The CMBR:** probes the recombination era, $t \sim 10^5$ yr, $z \sim 1100$, based on a well understood atomic and macroscopic physics
- **Nucleosynthesis:** probes the $t \sim 10^{-3}$ - 10^2 sec era, $z \sim 10^9$, compare the model predictions with observed abundances of the lightest elements, based on a well understood nuclear physics
- **Matter-antimatter asymmetry:** probes the baryogenesis era, $t \sim 10^{-6}$ sec, $z \sim 10^{12}$, but only in suggesting that some symmetry breaking did occur
- **Predictions of the inflationary scenario:** flatness, uniformity of CMBR, absence of monopoles, the right type of density fluctuation spectrum - it all supports the idea that inflation did happen, but does not say a lot about its detailed physics
- Cosmological observations can indicate or constrain physics well outside the reach of laboratory experiments

CMBR and the Recombination Era

Prediction of CMB is trivial in Hot Big Bang model:

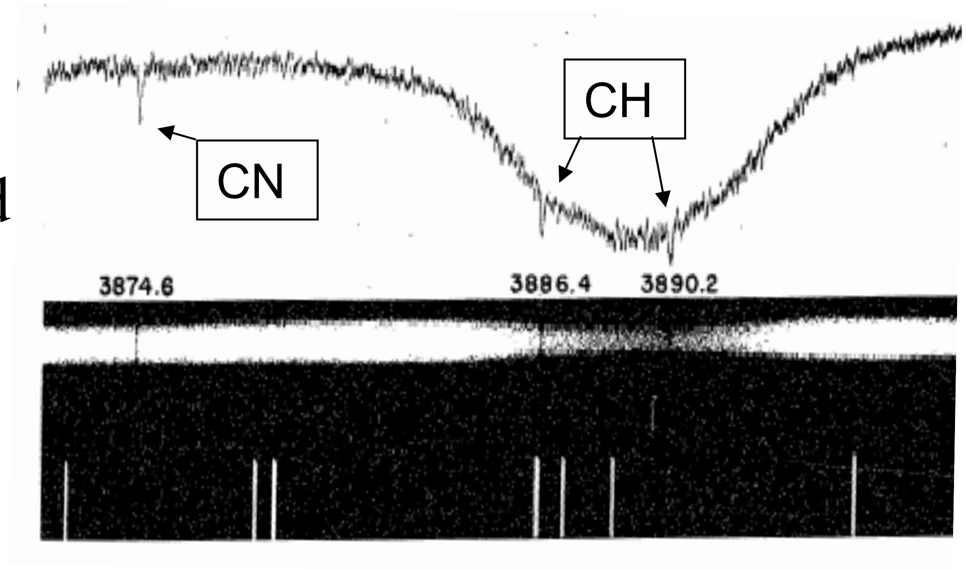
- Hot, ionised initial state should produce thermal radiation
- Photons decouple when universe stops being ionised (last scattering)
- Expansion by factor *a* cools a blackbody spectrum from *T* to *T/a*
- Therefore we should now see a cool blackbody background
  - Alpher and Herman, 1949, “A temperature now of the order of 5 K”
  - Dicke et al., 1965, “<40 K”
    - note that the Gamow, Alpher & Herman prediction had been nearly forgotten at this time!



The CMBR Disoveries

First seen in 1941 (yes, 1941!)

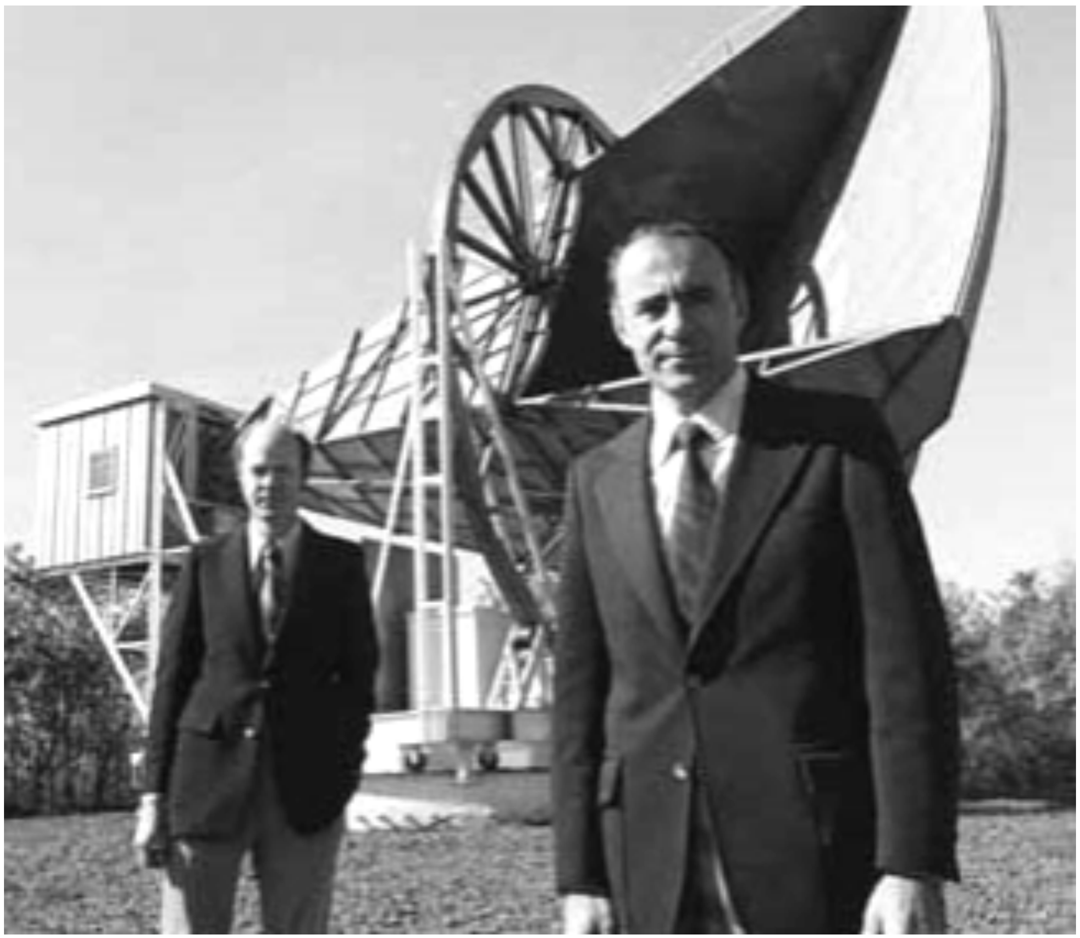
- Lines seen in stellar spectra identified as interstellar CH and CN (Andrew McKellar, theory; Walter Adams, spectroscopy)
- Comparison of lines from different rotational states gave “rotational temperature” of 2-3 K



- Unfortunately Gamow *et al*. did not have known about this
- Hoyle made the connection in 1950:

  "[the Big Bang model] would lead to a temperature of the radiation at present maintained throughout the whole of space much greater than McKellar's determination for some regions within the Galaxy."
- So, Penzias & Wilson made the recognized discovery in 1964

Discovery of the Cosmic Microwave Background (CMBR): A Direct Evidence for the Big Bang

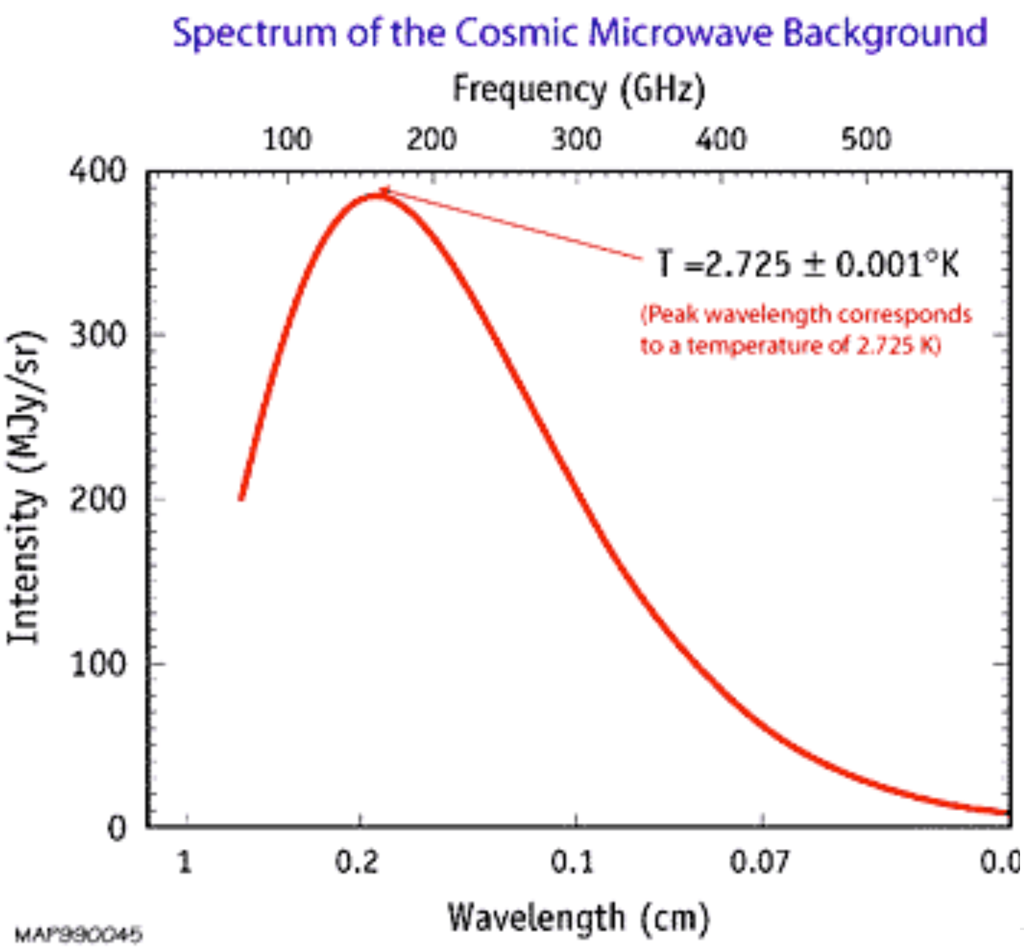


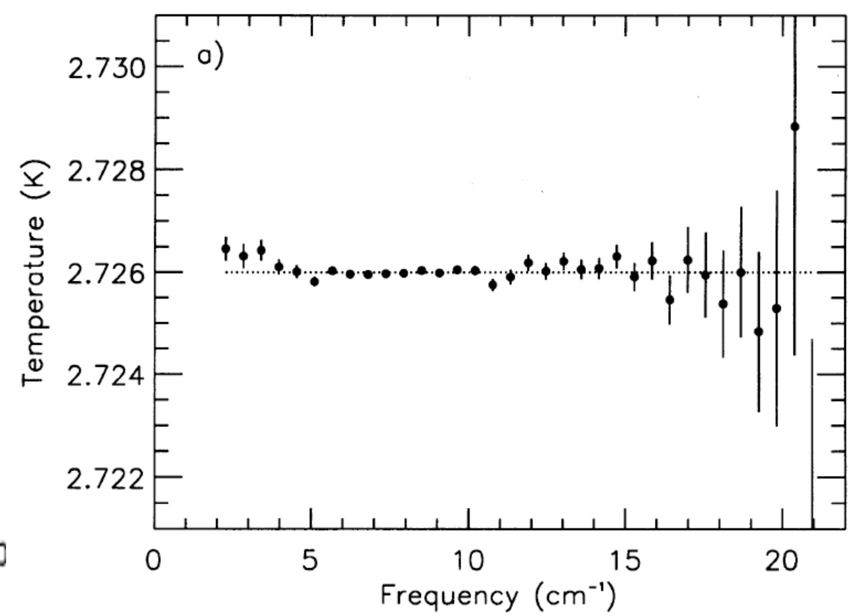
Arno Penzias &
Robert Wilson (1965)

Nobel Prize, 1978

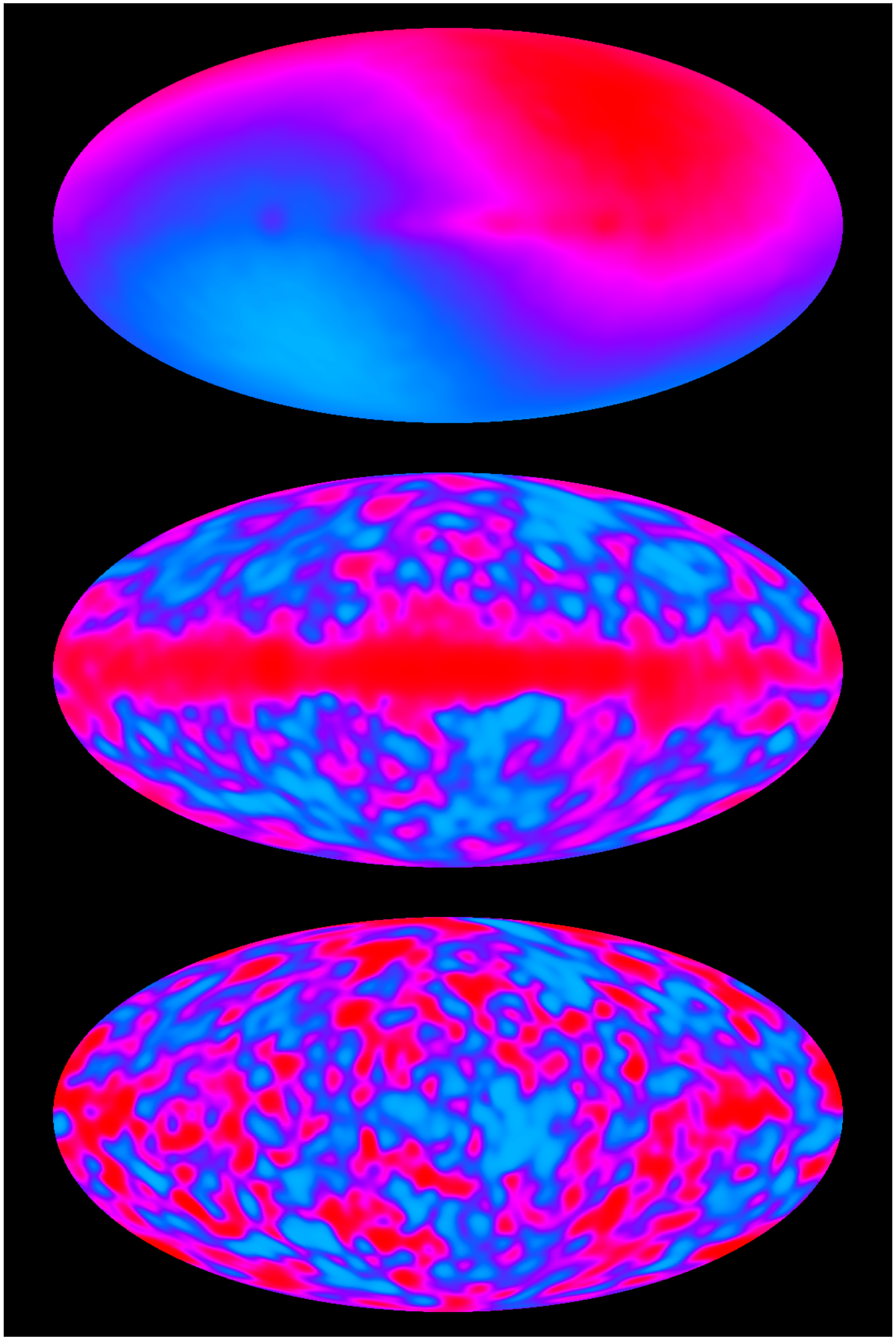
The CMBR Spectrum:
A Nearly Perfect Blackbody

Residuals from the BB strongly limit possible energy injection (e.g., from hypothetical decaying DM particles) during and after the recombination - no new physics here…





CMBR Sky From COBE



Mean subtracted;
Dipole anisotropy visible

Dipole subtracted

Galaxy emission subtracted;
primordial density fluctuations visible

Temperature of Recombination

Mean photon energy: $\langle E \rangle \sim 3k_B T$

Ionisation energy of H: $E = 13.6\,\mathrm{eV}$

Photoionisation Temperature: $T = \dfrac{13.6\,\mathrm{eV}}{3k_B} = 50000\mathrm{K}$

But there are many more photons than H ions: $n_\gamma \approx 10^9 n_p$

Thus, the T can be lower and have enough photons with high enough energies to ionize H!

Boltzmann distribution: $n_\gamma(>E) \propto \exp\left(-E/k_B T\right)$

So the actual T of recombination is:

$$T = \frac{13.6\,\mathrm{eV}}{3k_B 9\ln(10)} = 2500\mathrm{K}$$

And thus, $z_{rec} \sim 1100$

The Extent of Recombination

This phase transition (ionized to neutral gas) has a finite thickness: most of the plasma recombines before the last scattering, which is the CMBR photosphere we see

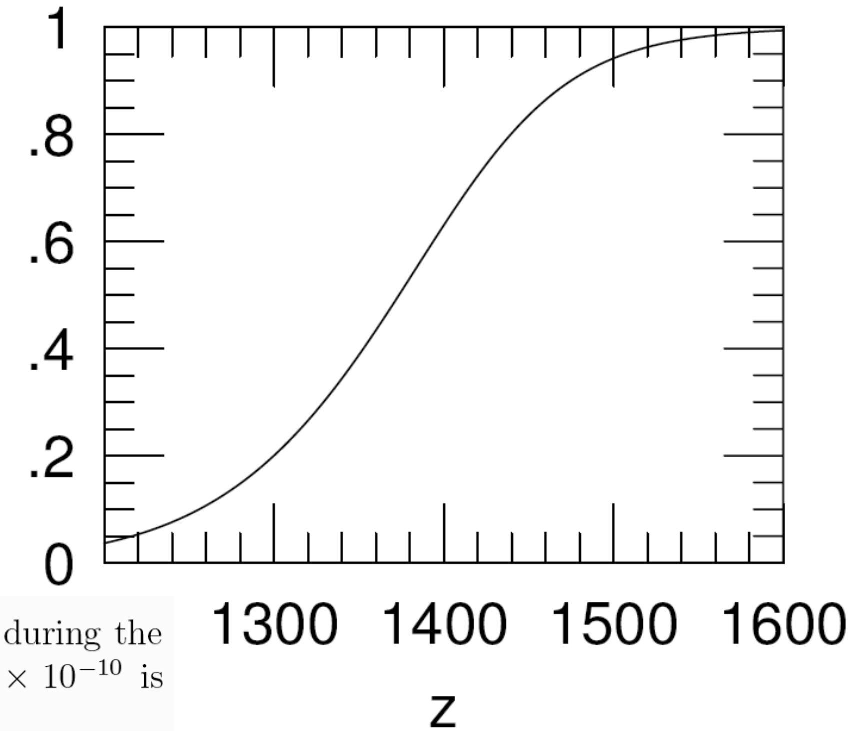
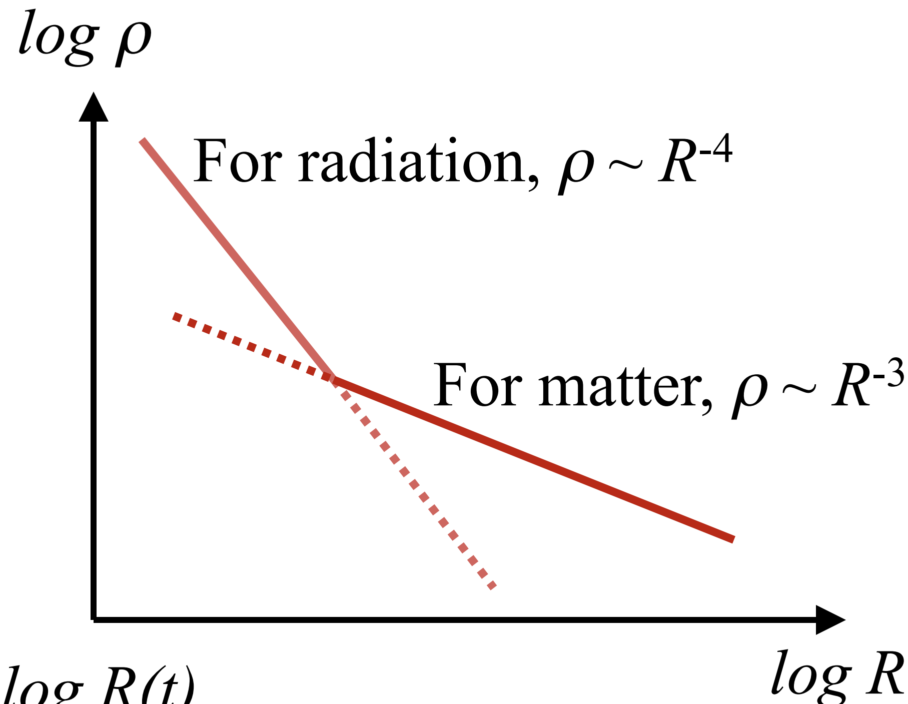


Figure 9.4: The fractional ionization X as a function of redshift during the epoch of recombination. A baryon-to-photon ratio of $\eta = 5.5 \times 10^{-10}$ is assumed.

Table 9.1: Events in the early universe

event	redshift	temperature (K)	time (megayears)
radiation-matter equality	3570	9730	0.047
recombination	1370	3740	0.24
photon decoupling	1100	3000	0.35
last scattering	1100	3000	0.35

Radiation vs. Matter Dominance



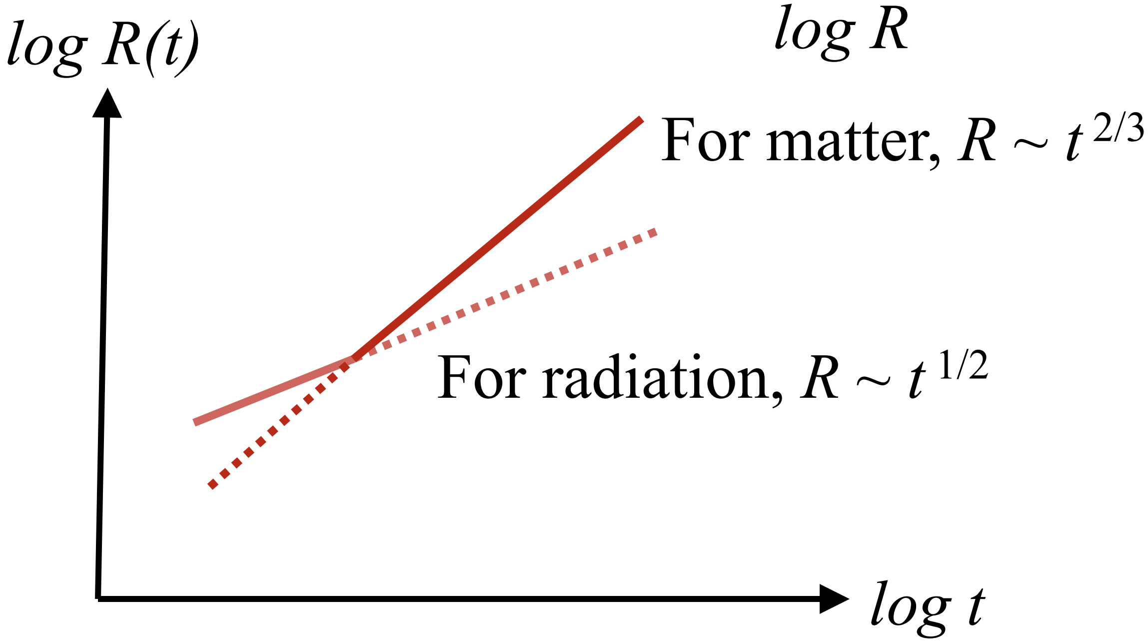
Computing the matter-energy equality redshift:

$\rho_{0,CMB} = 4\sigma/c^3\ T_{CMB}{}^4$

$\rho_{0,m} = \Omega_{0,m}\ \rho_{0,crit}$

$\rho_{0,CMB}\,(1+z_{EQ})^4 = \rho_{0,m}\ (1+z_{EQ})^3$

gives $z_{EQ} \sim 5000$



Handy formula for the radiation-dominated regime:

$$\left(\frac{1\,\text{sec}}{\text{t}}\right)^{1/2} \sim \frac{k_B T}{2\ \text{MeV}}$$

Next:
The Big Bang Nucleosynthesis (BBNS)