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Chemical Evolution of the Universe

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Origin of Chemical Elements

- Big Bang Nucleosynthesis: *t ~ 3* min

  ^{1}H ^{2}D ^{3}He ^{4}He … ^{7}Li

- Fusion in stars: *We are stardust!*

  … ^{12}C ^{14}N ^{16}O … ^{56}Fe

- Fusion in supernova explosions ($M_* > 8\ M_{sun}$)

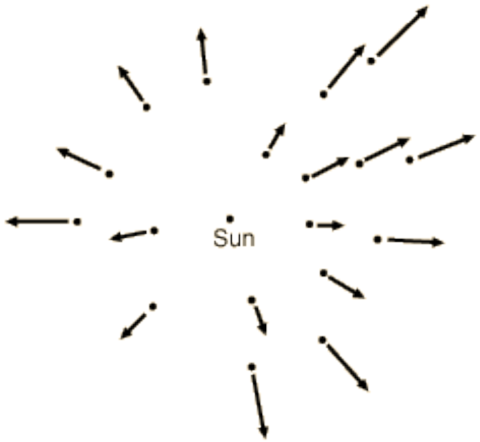
  … ^{56}Fe … ^{235}U

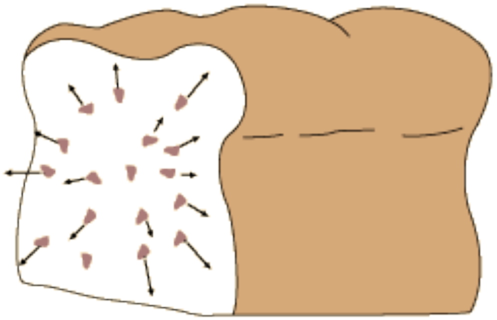
- Abundances rise as each generation of stars pollutes the interstellar medium (ISM).

Cosmology Lite

- 1925 Galaxy redshifts $\lambda = \lambda_0 \left(1 + z \right)$ $V = c\,z$
  - Isotropic expansion. (Hubble law $V = H_0\, d$)
  - Finite age. (t_0 =13 x 10^9 yr)
- 1965 Cosmic Microwave Background (CMB)
  - Isotropic blackbody. T_0 = 2.7 K
  - Hot Big Bang
- 1925 General Relativity Cosmology Models :
  - Radiation era: $R \sim t^{1/2}$ $T \sim t^{-1/2}$
  - Matter era: $R \sim t^{2/3}$ $T \sim t^{-2/3}$
- 1975 Big Bang Nucleosynthesis (BBN)
  - light elements (^{1}H … ^{7}Li) $t \sim 3$ min $T \sim 10^9$ K
  - primordial abundances (75% H, 25% He) as observed!

Isotropic Expansion





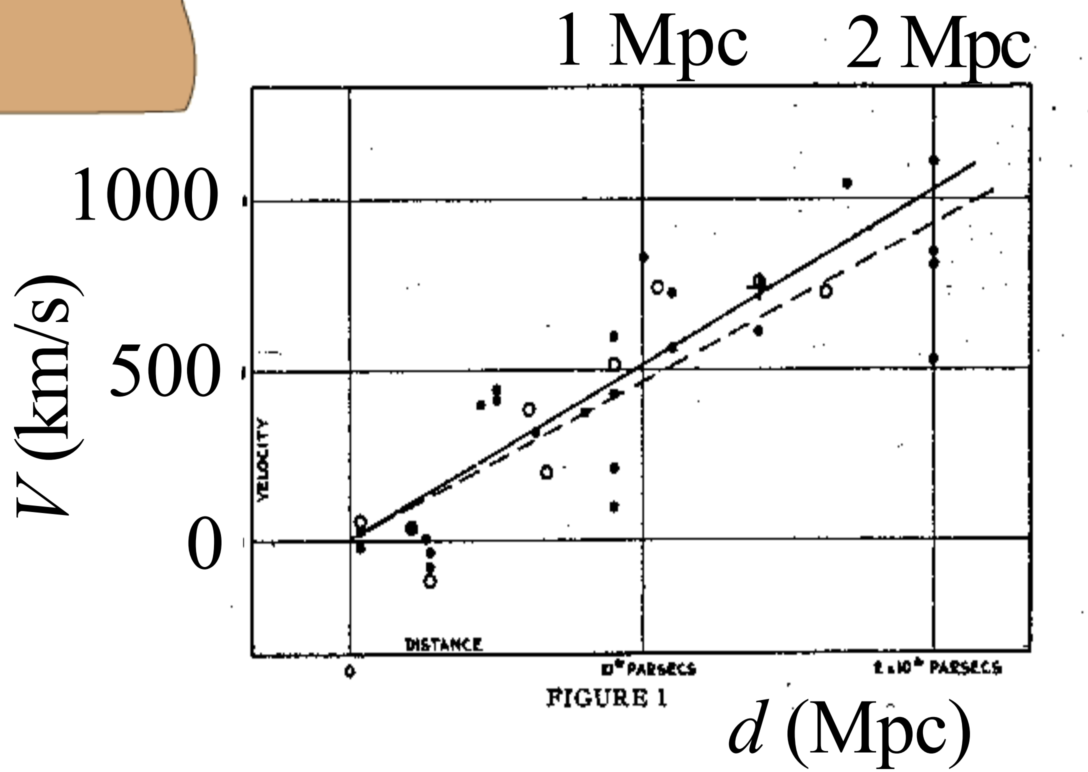
No visible edge.
No centre of expansion.

Hubble law :

$$V = H_0\, d$$

Hubble constant :

$$H_0 \approx 500 \text{ km s}^{-1}\text{Mpc}^{-1}$$

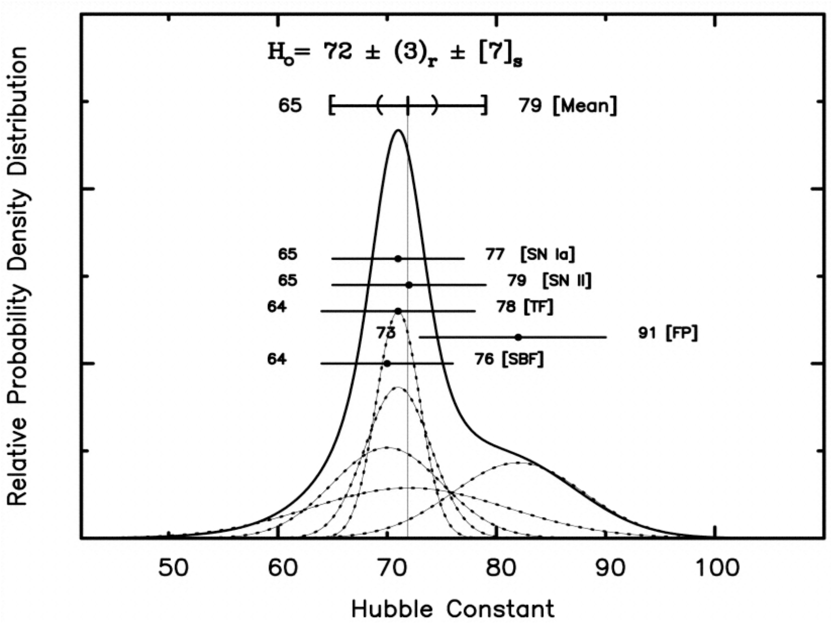


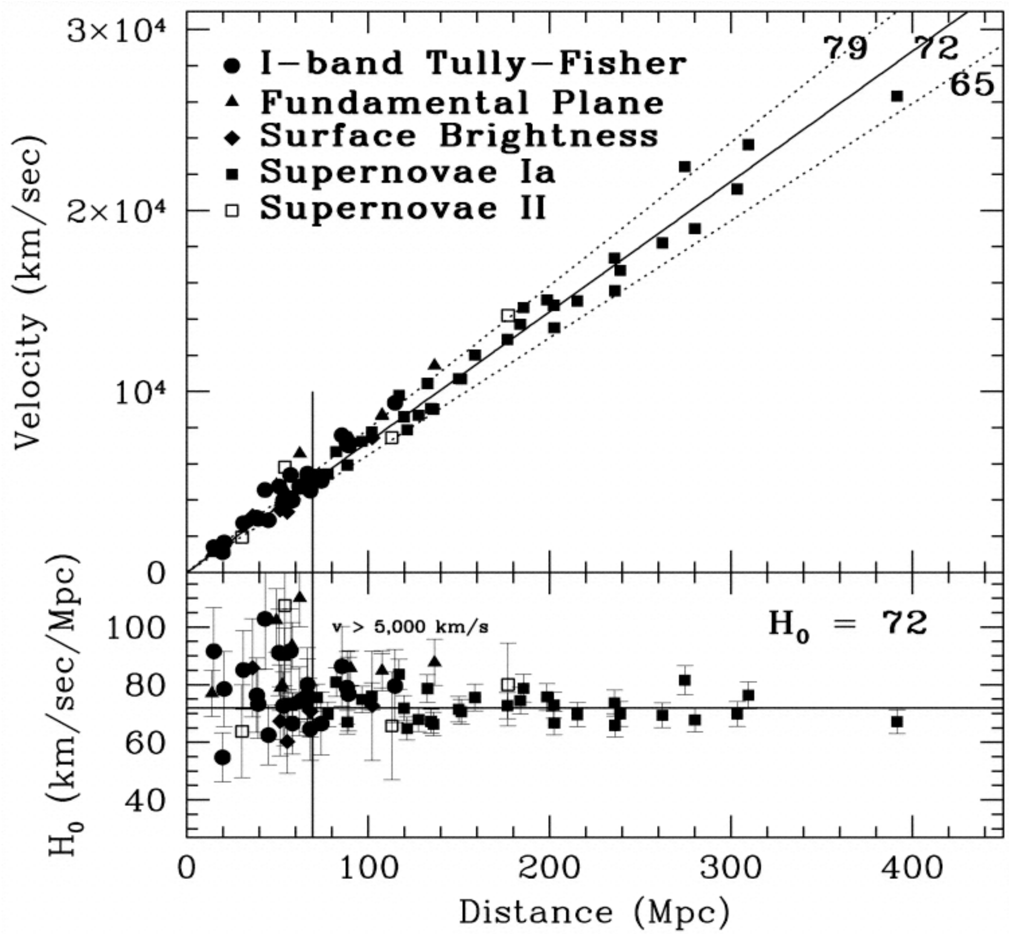
WRONG ! Extinction by interstellar dust then unknown.
Hubble's distances were 10x too small.

HST Key Project

$$H_0 \approx 72 \pm 3\,(\pm 7) \quad \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

Freedman et al.
2001 ApJ 553, 47.





Hubble Law --> Finite age.

$$V = H_0\, d$$

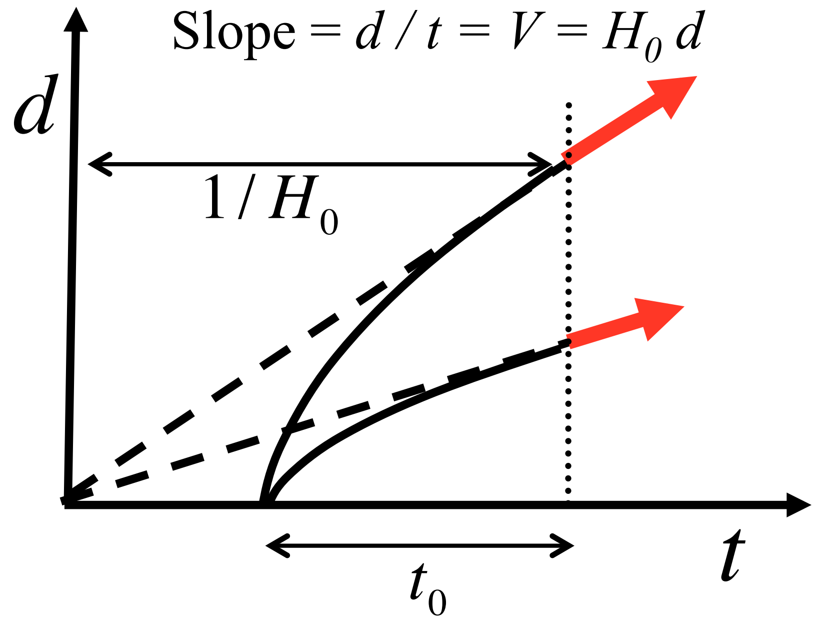
$$t_0 \sim \frac{d}{V} = \frac{1}{H_0} \quad = \left(\frac{1\ \text{Mpc}}{72\ \text{km/s}}\right)\left(\frac{3\times10^{19}\ \text{km}}{\text{Mpc}}\right)\left(\frac{1\ \text{yr}}{3\times10^{7}\ \text{s}}\right)$$

$$\approx 13\times10^{9}\ \text{yr} = 13\ \text{Gyr}.$$

Gravity decelerates:

Matter-dominated: $d \propto t^{2/3}$

$$t_0 \approx \frac{2}{3}\frac{1}{H_0}.$$



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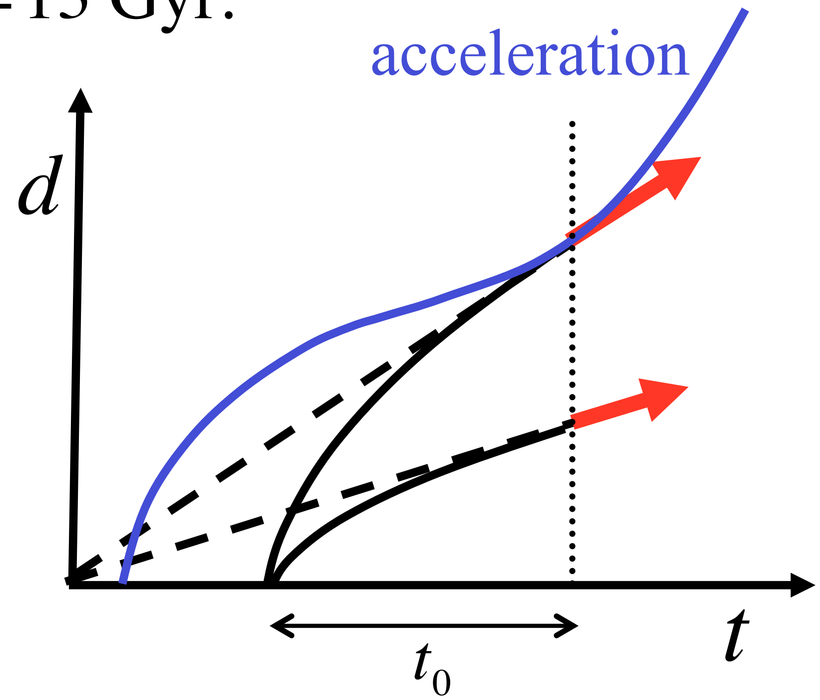
$$\approx 13\times10^{9}\ \mathrm{yr} = 13\ \mathrm{Gyr.}$$

Gravity decelerates:

Dark Energy accelerates

$$t_0 > \frac{2}{3}\frac{1}{H_0}\,.$$



Self-assembly of compact structures

Universe expands and cools.

4 forces 4 phase transitions when $kT \sim E$

elementary particle soup (quarks, gluons, leptons, bosons)

1. ***Strong force*** (quarks exchange gluons) :

quarks -> hadrons (baryons (qqq), mesons ($q\bar{q}$))

e.g. protons and neutrons ($T \sim 10^{12}$ K, $t \sim 10^{-4}$ s)

2. ***Weak force*** (exchange of vector bosons W^+, W^-, Z^0) :

neutrons -> protons

baryons -> atomic nuclei ($\sim 10^9$ K, ~ 3 min)

3. ***Electro-magnetic force*** (photons) :

nuclei + electrons -> neutral atoms (3000 K, 3×10^5 yr)

4. ***Gravity*** (gravitons):

galaxies of stars, some with planets, some with life.

(--> black holes --> evaporate to elementary particles.)

Cosmological Models

Assume a Universe filled with uniform density fluid.
[OK on large scales > 100 Mpc]

Density: $\rho = \Omega\, \rho_c$ Energy density: $\varepsilon = \rho\, c^2$

Critical density: $$\rho_c \equiv \frac{3\, H_0^{\ 2}}{8\pi\, G} \approx 10^{-26}\text{kg m}^{-3} \approx \frac{1.4\times 10^{11}\text{Msun}}{(\text{Mpc})^3}$$

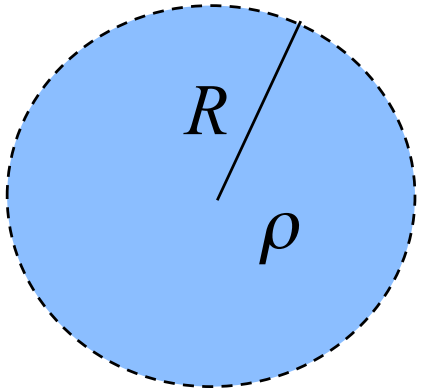
3 components:

1. ***Radiation*** $\Omega_R \approx 5\times 10^{-5}$
2. ***Matter*** $\Omega_M \sim 0.3$ { "Dark Matter" $\Omega_D \sim 0.26$; baryons $\Omega_B \sim 0.04$
3. "***Dark Energy***" $\Omega_\Lambda \sim 0.7$

Total $\Omega = \Omega_R + \Omega_M + \Omega_\Lambda = 1$

Only ~4% is matter as we know it!

Critical Density



- Newtonian analogy:

escape velocity:

$$V_{esc}^{\;2} = \frac{2\,G\,M}{R} = \frac{2\,G}{R}\left(\frac{4\pi\,R^3\rho}{3}\right) = \frac{8\pi\,G\,R^2\rho}{3}$$

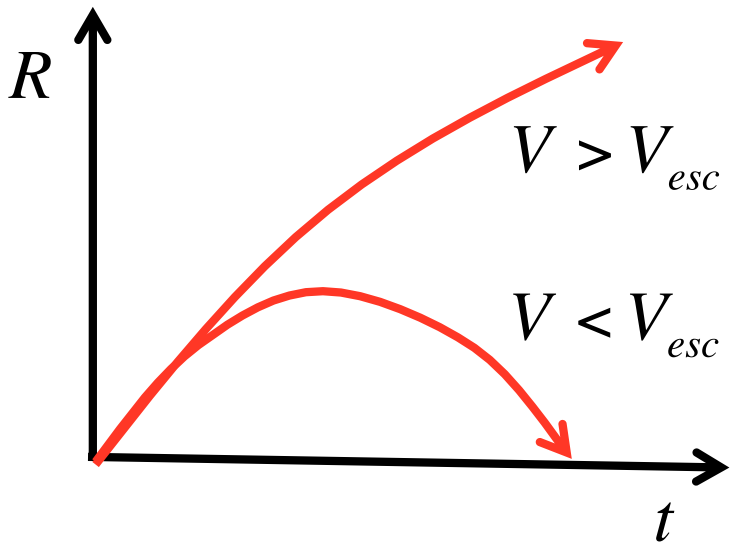
Hubble expansion:

$$V = H_0\,R$$

critical density:

$$\left(\frac{V_{esc}}{V}\right)^2 = \frac{8\pi\,G\rho}{3\,H_0^{\;2}} = \frac{\rho}{\rho_c}$$

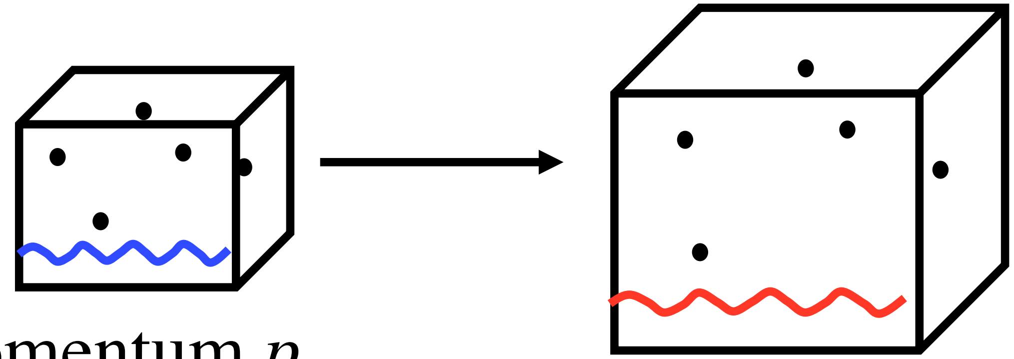
$$\rho_c = \frac{3\,H_0^{\;2}}{8\pi\,G}$$



Energy Density of expanding box

volume R^3

N particles



particle mass m momentum p

energy $E = h\nu = \sqrt{m^2c^4 + p^2c^2} = m\,c^2 + \frac{p^2}{2m} + \ldots$

Radiation: ($m = 0$)

Hot Matter: ($m > 0, \; p >> mc$)

$\lambda \propto R$ (wavelengths stretch) :

$$E = h\,\nu = \frac{h\,c}{\lambda} \propto R^{-1}$$

$$\varepsilon_R = \frac{N\,h\,\nu}{R^3} \propto R^{-4}$$

Cold Matter: ($m > 0, \; p << mc$)

$$E \approx m\,c^2 = \text{const}$$

$$\varepsilon_M \approx \frac{N\,m\,c^2}{R^3} \propto R^{-3}$$

3 Eras: radiation…matter…vacuum

radiation: $\rho_R \propto R^{-4}$

matter: $\rho_M \propto R^{-3}$

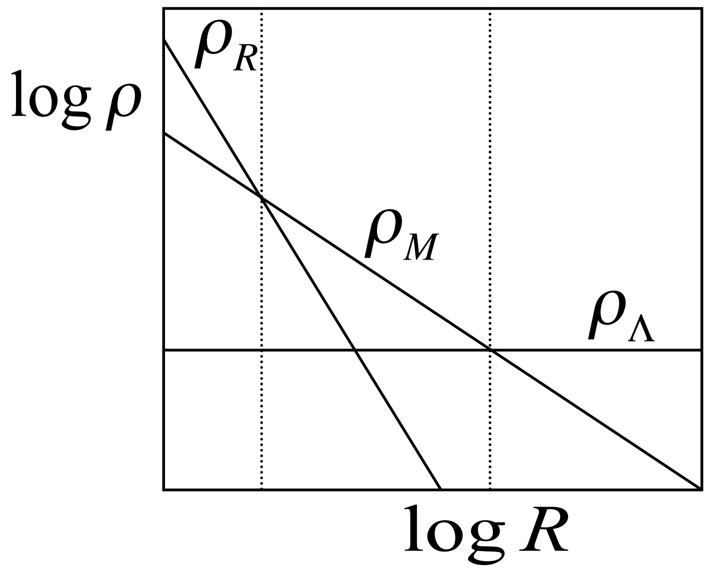
vacuum: $\rho_\Lambda = \text{const}$

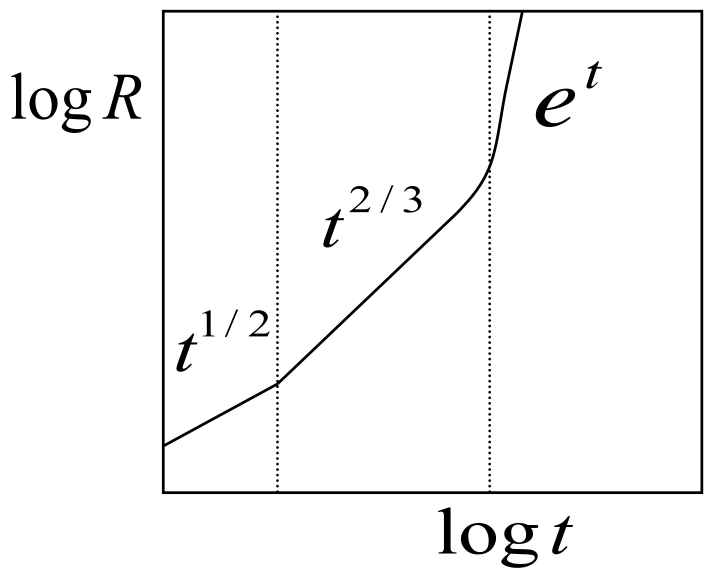
$$a \equiv \frac{R}{R_0} = \frac{1}{1+z} \qquad z = \text{redshift}$$

$$\rho = \frac{\rho_{R,0}}{a^4} + \frac{\rho_{M,0}}{a^3} + \rho_\Lambda$$

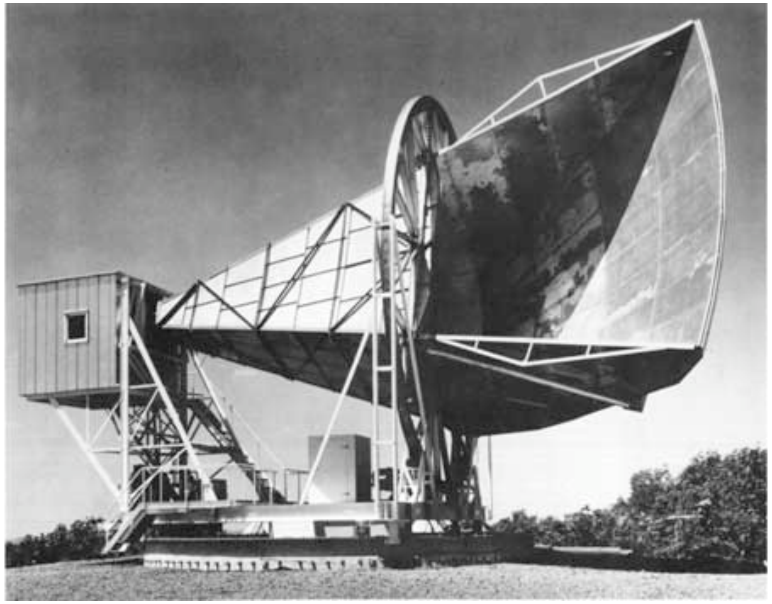
$\rho_R = \rho_M$ at $a \sim 10^{-4}$ $\quad t \sim 10^4$ yr

$\rho_M = \rho_\Lambda$ at $a \sim 0.7$ $\quad t \sim 10^{10}$ yr





1965 The Bell Lab antenna

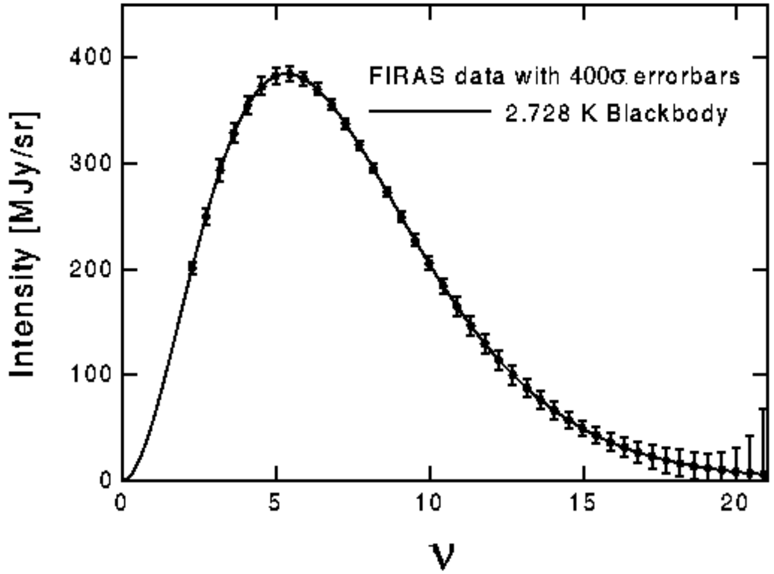


Penzias & Wilson

Discovered the CMB

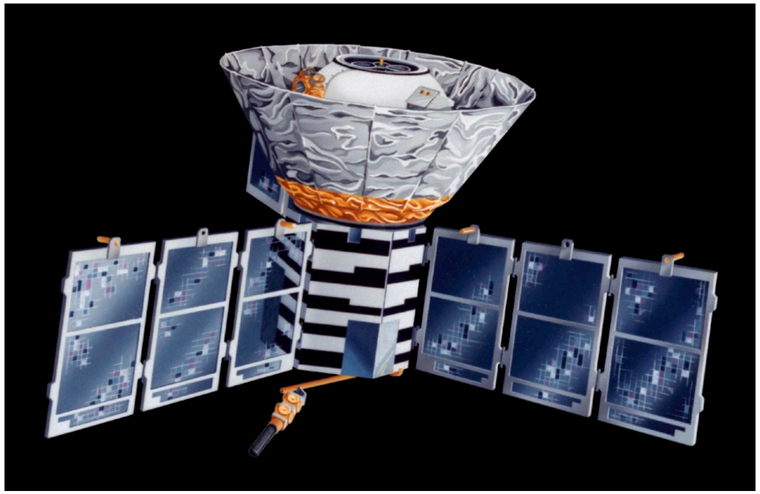
The CMB spectrum

A perfect Blackbody!



1992 NASA - COBE

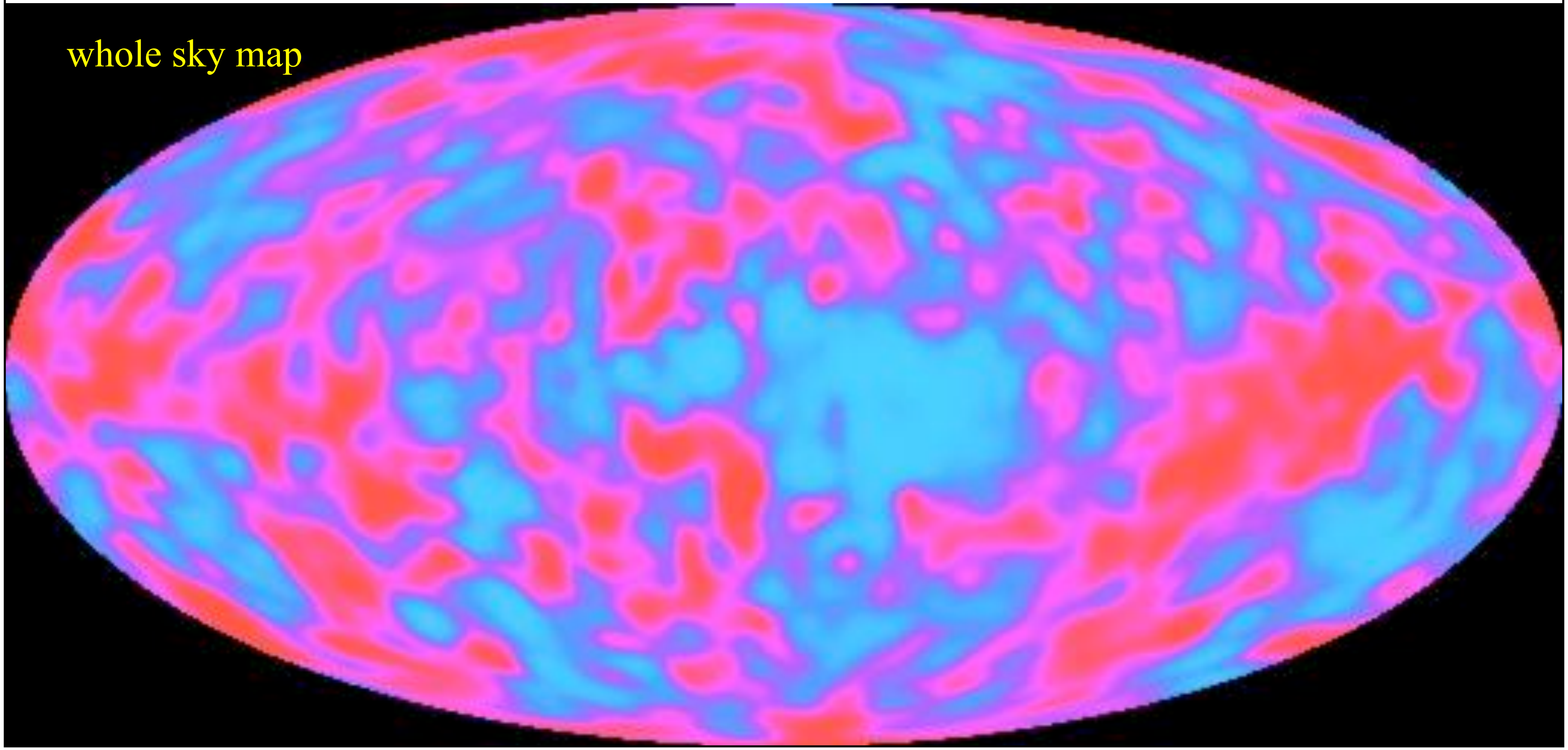
COsmic Background Explorer



1992 COBE

temperature ripples: $\frac{\Delta T}{T} \sim 10^{-5}$

angular resolution: $\Delta\theta \approx 7^{\circ}$

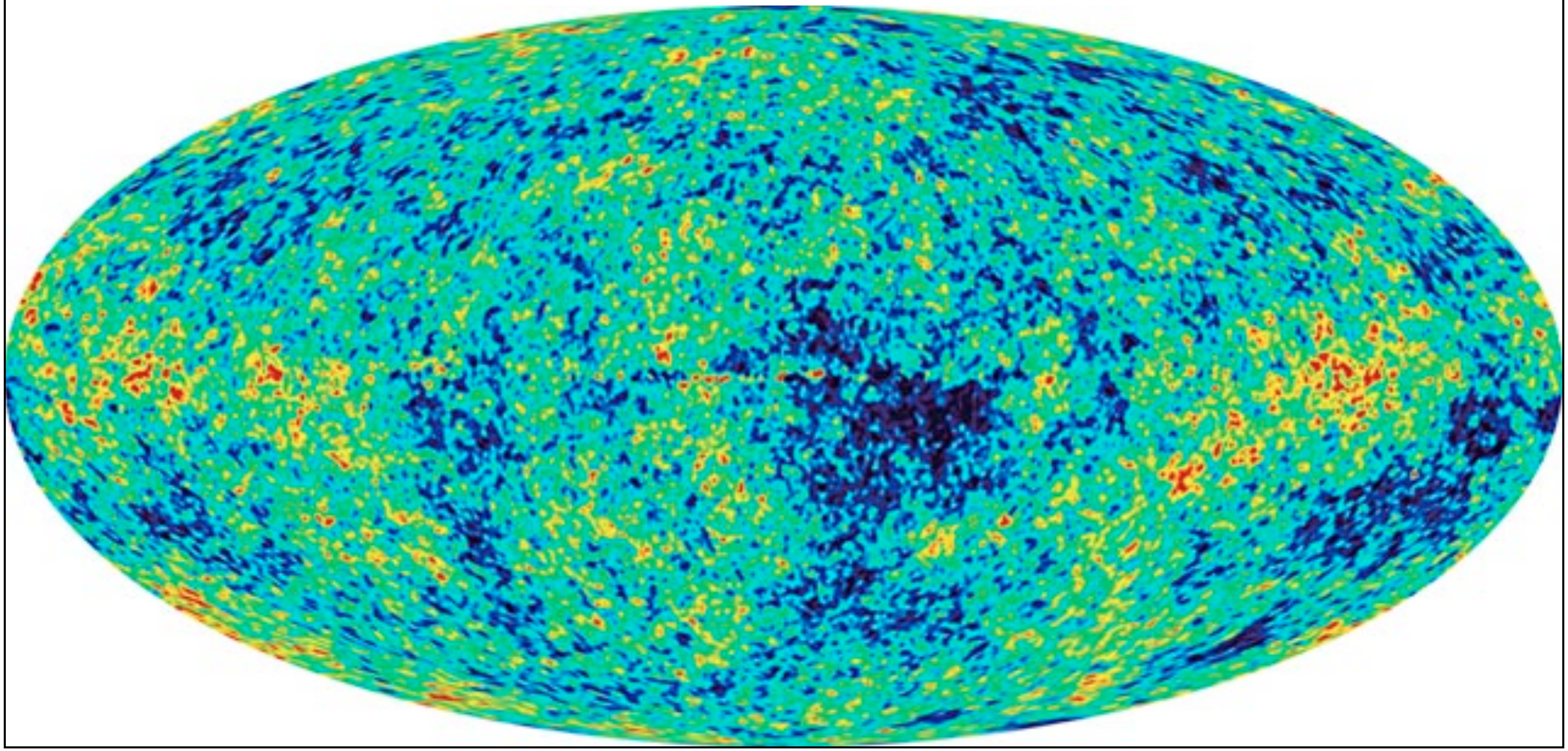


2004 WMAP

Wilkinson Microwave Anisotropy Probe

preferred angular scale: $\Delta\theta \approx 1^{\circ} \Rightarrow \Omega \approx 1.0$

The seeds of galaxies



Cosmic Microwave Background (CMB)

Blackbody temperature $T = 2.728\text{ K}$

energy density $\varepsilon_\nu = \dfrac{8\pi\, h}{c^3} \dfrac{\nu^3}{\exp(h\nu/kT) - 1}$

$$\varepsilon = \int \varepsilon_\nu \,\mathrm{d}\nu = \alpha\, T^4 \approx 4.2 \times 10^{-14}\text{ J m}^{-3}$$ (Tut. sheet 1)

mean photon energy $\overline{h\nu} \approx 3\,k\,T = 7 \times 10^{-4}\text{ eV}$

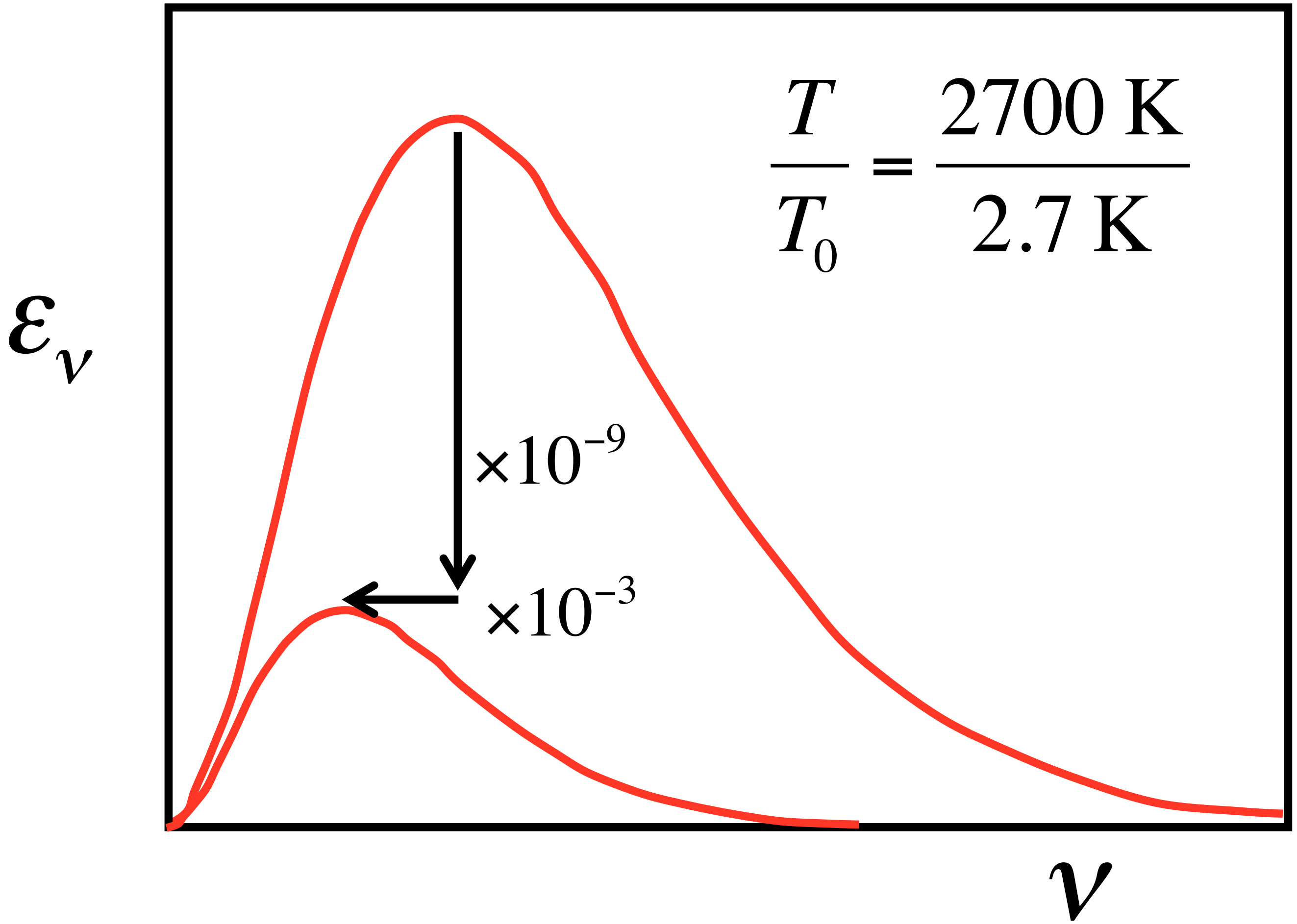
photon density $n_\gamma = \varepsilon / h\nu \approx 4 \times 10^8 \dfrac{\text{photons}}{\text{m}^3}$

baryon density $n_B = \rho_B / m_p \approx 0.2 \dfrac{\text{baryons}}{\text{m}^3}$

ratio $\dfrac{\text{photons}}{\text{baryons}} \sim 10^9$ Why?

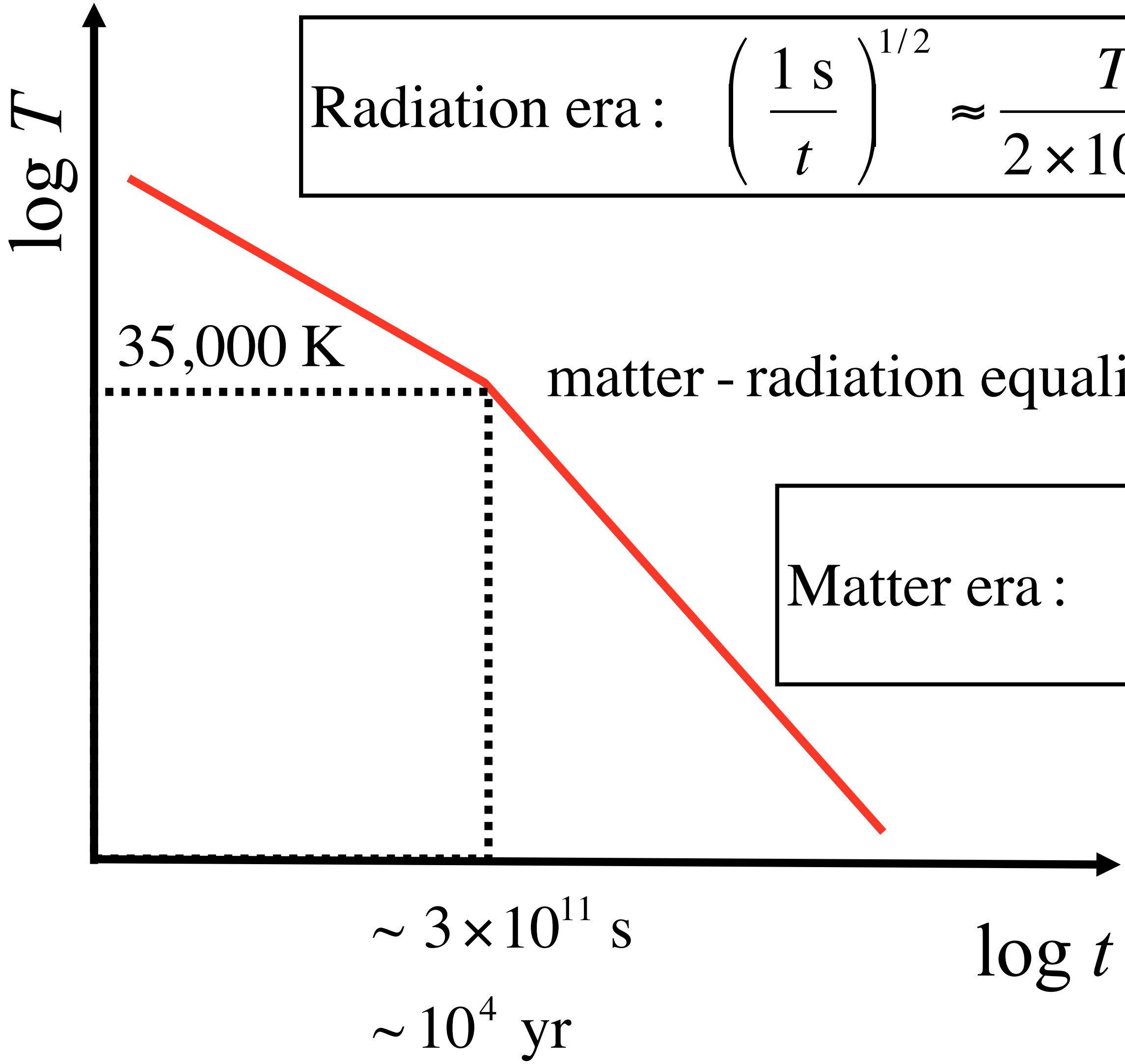
Adiabatic Expansion preserves the Blackbody spectrum

$$T \propto \frac{1}{R} \qquad h\nu \propto T \qquad \varepsilon \propto T^4$$



Cooling History: T(t)

$$\text{Radiation era:} \quad \left(\frac{1\ \text{s}}{t}\right)^{1/2} \approx \frac{T}{2\times10^{10}\,\text{K}} = \frac{k\,T}{2\ \text{MeV}}$$



matter - radiation equality : $\rho_M = \rho_R$

$$\text{Matter era:} \quad \left(\frac{10^{10}\ \text{yr}}{t}\right)^{2/3} = \frac{T}{2.7\ \text{K}}$$

In the early Universe
($kT > E$) photons break up atomic nuclei
binding energies:

Deuterium ~ 2 MeV $T \sim 10^9$ K $t \sim 100$ s

Iron ~ 7 MeV $T \sim 10^{10}$ K $t \sim 1$ s

Earlier still, neutrons and protons break into quarks

mass energies: $T \sim 10^{12}$ K $t \sim 10^{-4}$ s

neutron ~ 939.6 MeV

proton ~ 938.3 MeV

This takes us back to the quark soup!

Next time we will run the clock forward!