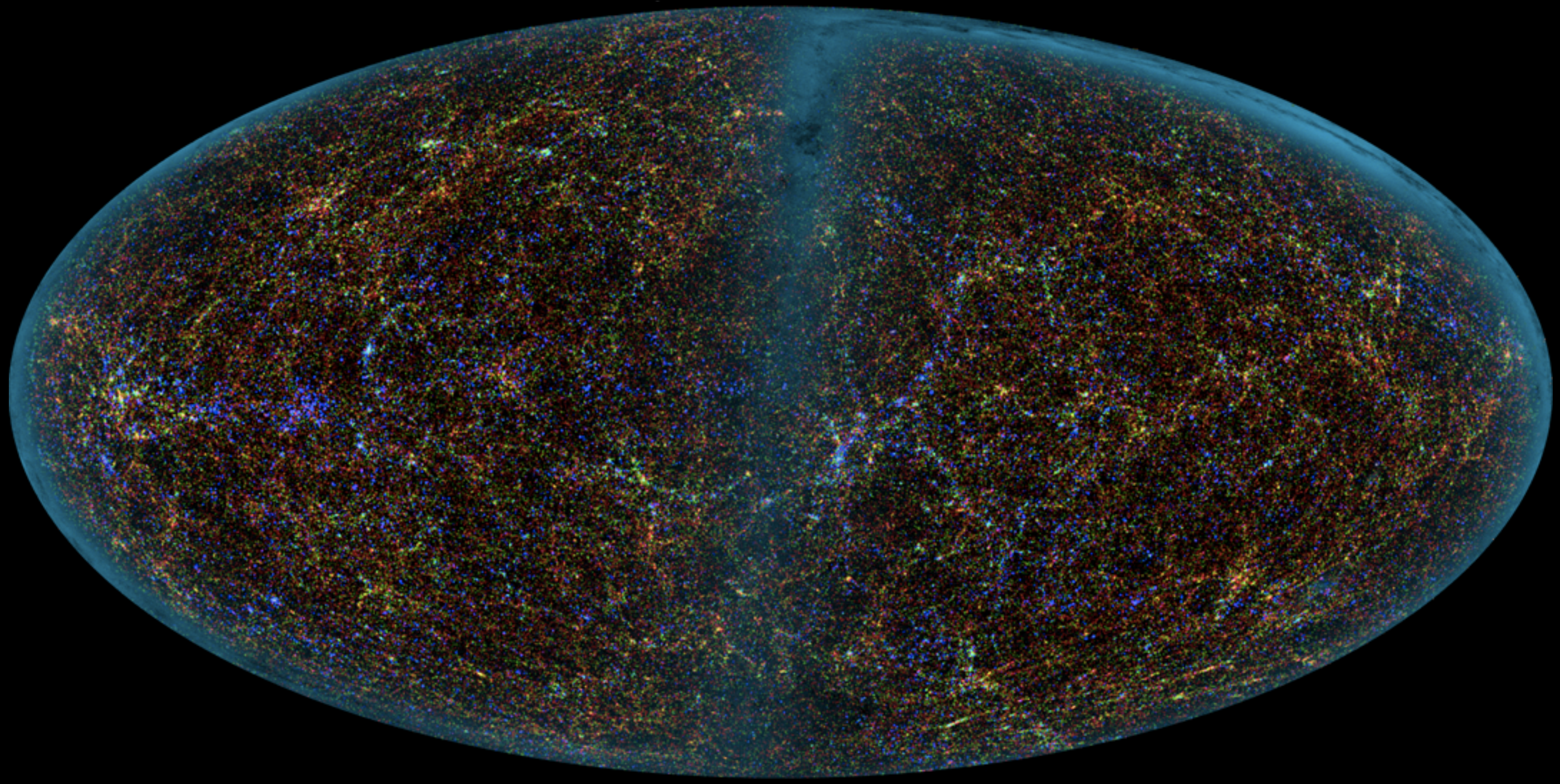
Cosmology

and Large Scale Structure



Today
Empirical Pillars
of the Hot Big Bang

Relic Radiation as the CMB

Two basic laws

$$V = H_0 D_{\text{proper}} \qquad \text{now}$$

$$\frac{a_0}{a} = 1 + z$$

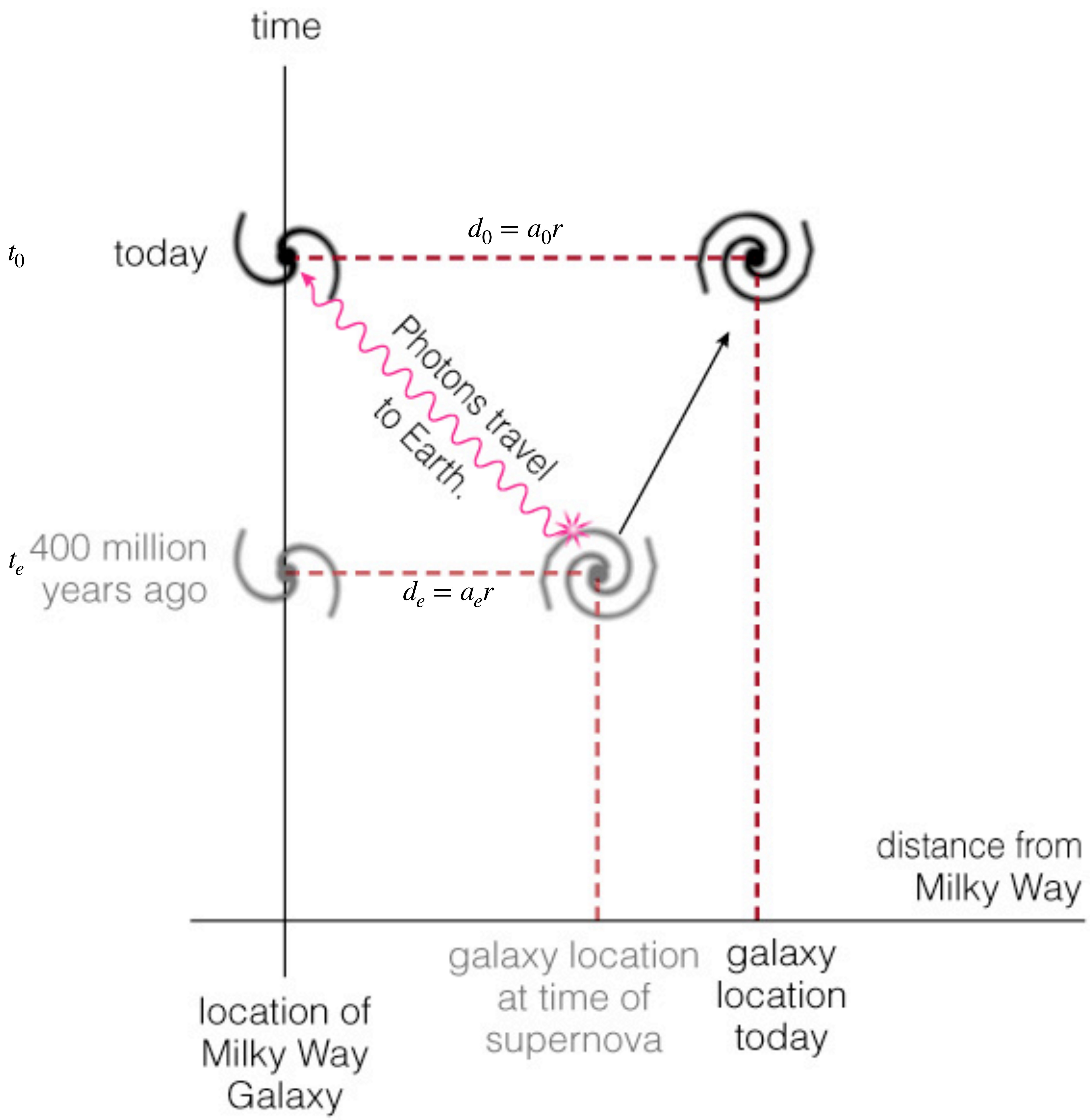
t_0 is now, so $a(t_0) = 1$ at $z = 0$

The (1+z) corrects the current proper distance to the path length travelled by a photon to provide the Euclidean-equivalent luminosity distance.

$$d_L = (1 + z) D_{\text{proper}}$$

The relation V = cz is only approximately valid for small z. In general, one needs the relativistic version

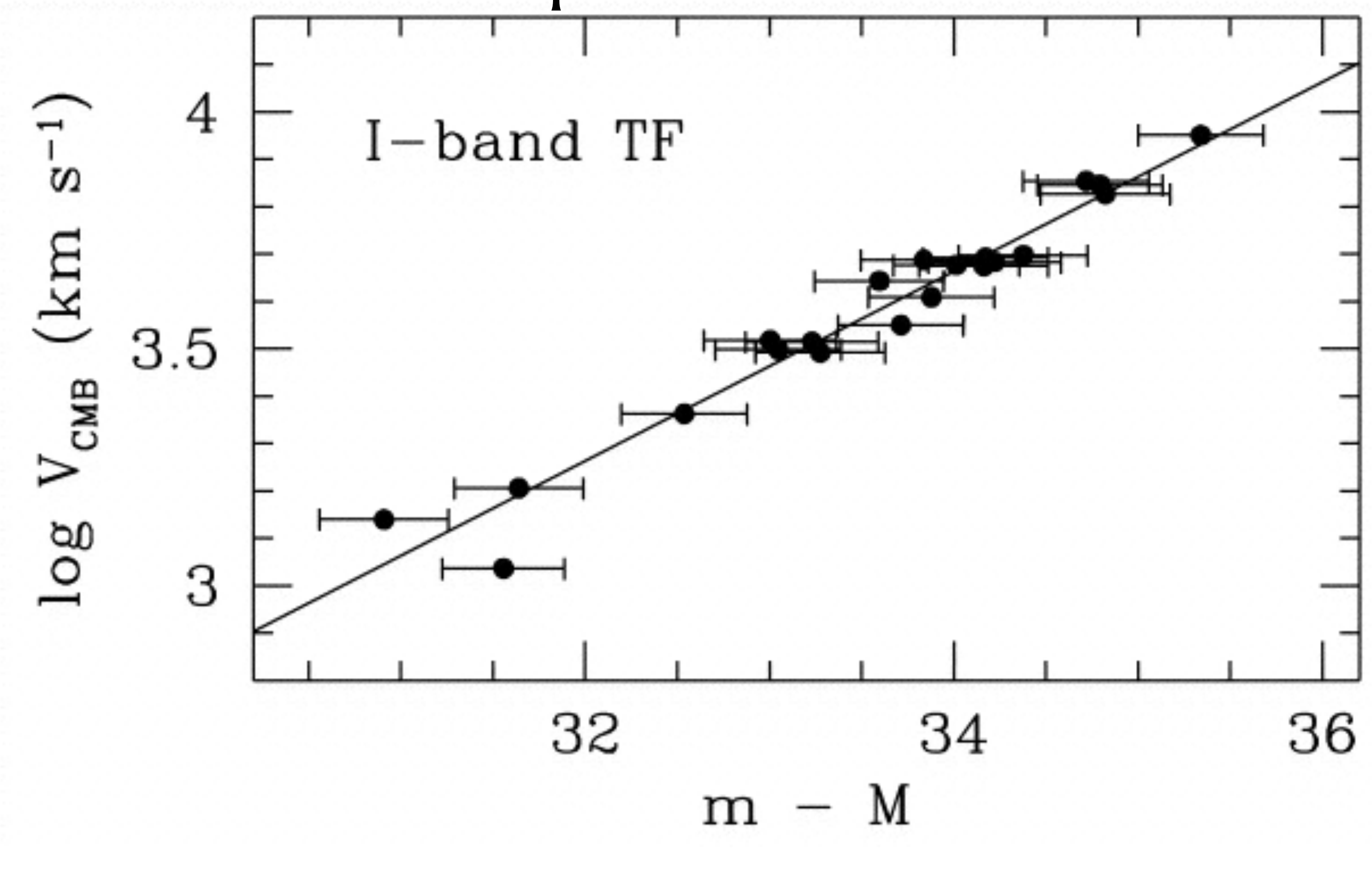
$$\frac{V}{c} = \frac{z^2 + 2z}{z^2 + 2z + 2}$$



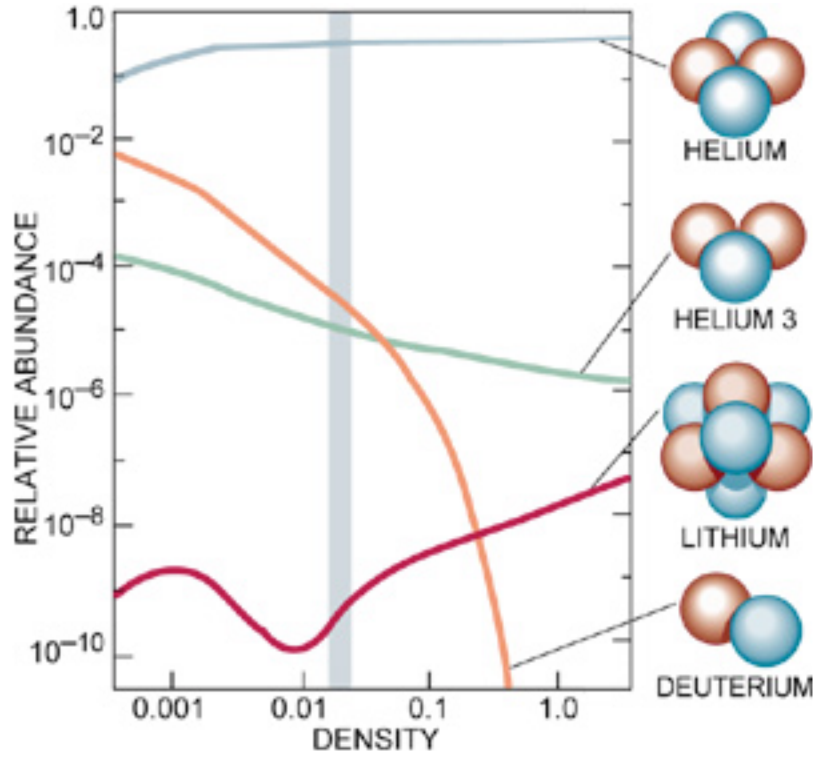
Empirical Pillars of the Hot Big Bang

1. Hubble Expansion — Hubble (1930)
2. Big Bang Nucleosynthesis (BBN) — Alpher & Gamow (1948) $\alpha\beta\gamma$ paper
3. Cosmic Microwave Background (CMB) — Penzias & Wilson; Peebles & Dicke (1965)

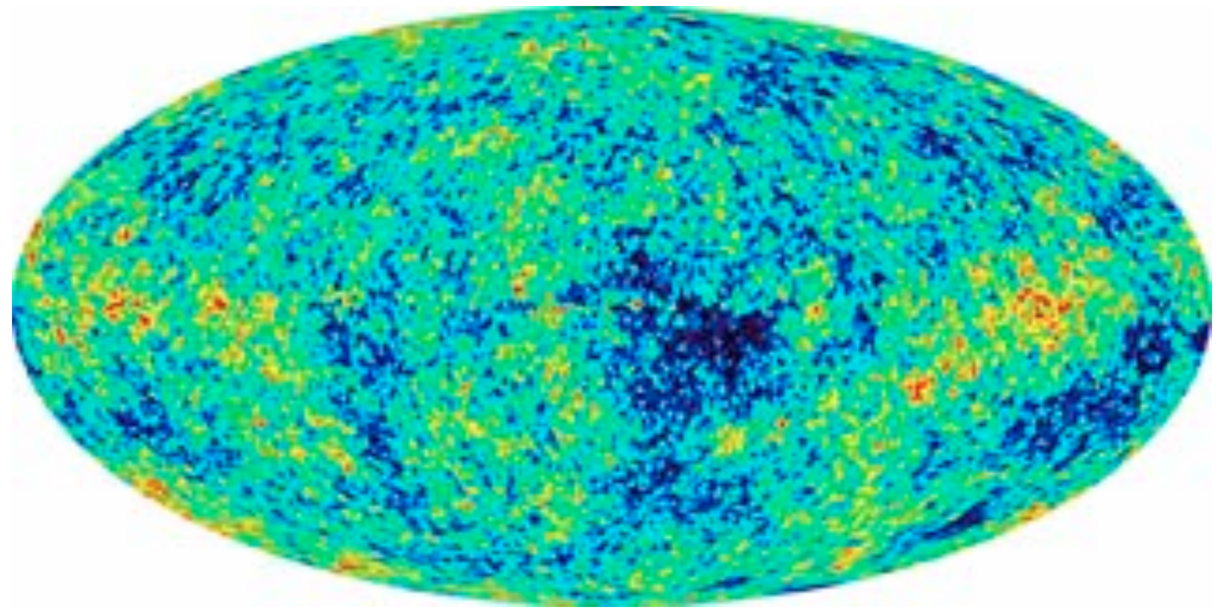
Hubble expansion



BBN
t ~ 3 minutes

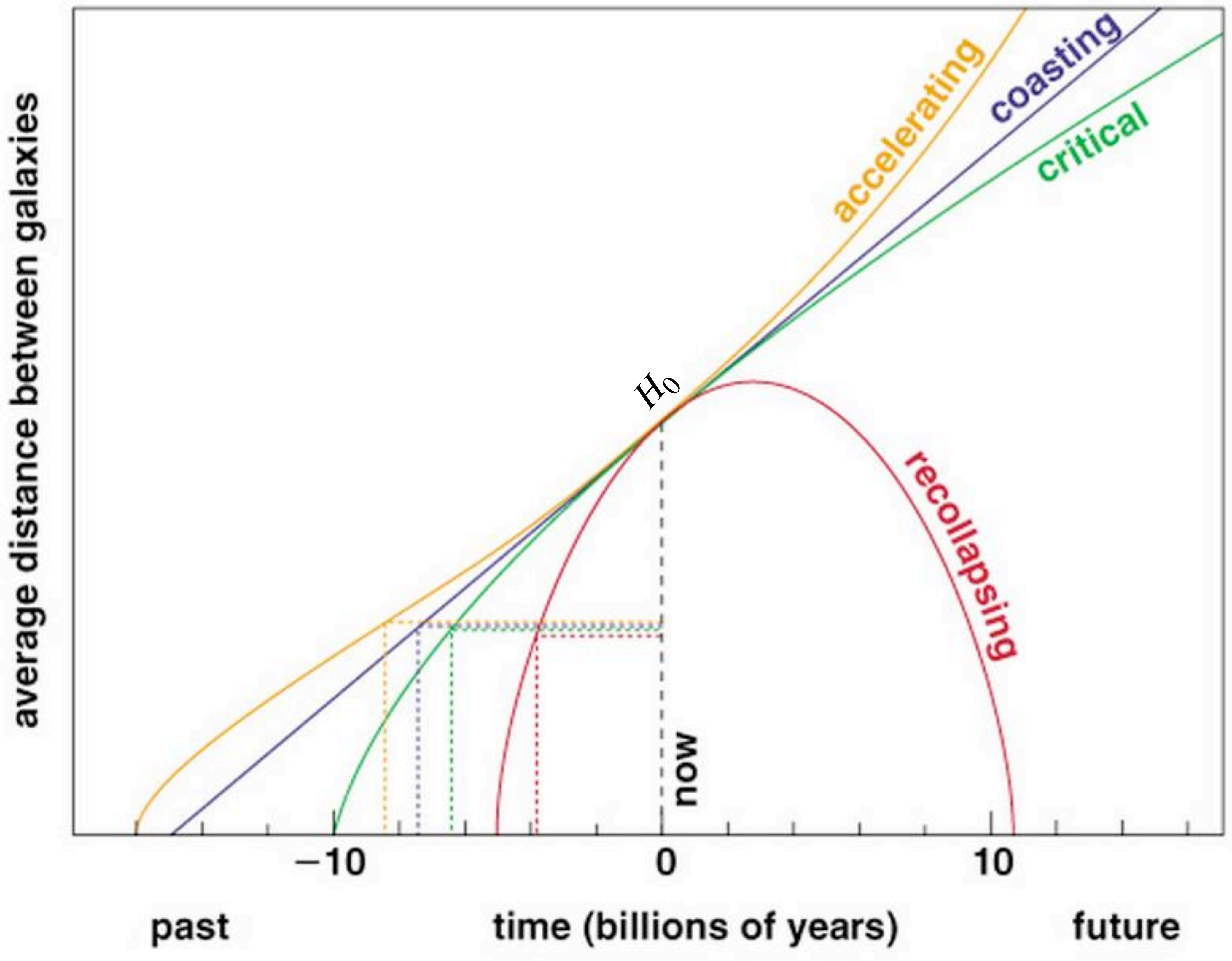


CMB
z = 1090
t = 380,000 yr



All expansion histories point to a dense, hot beginning - the **Hot Big Bang**

$a(t)$



t

Matter (non-relativistic "dust") dilutes as the volume expands:

$$\rho_m \sim a^{-3}$$

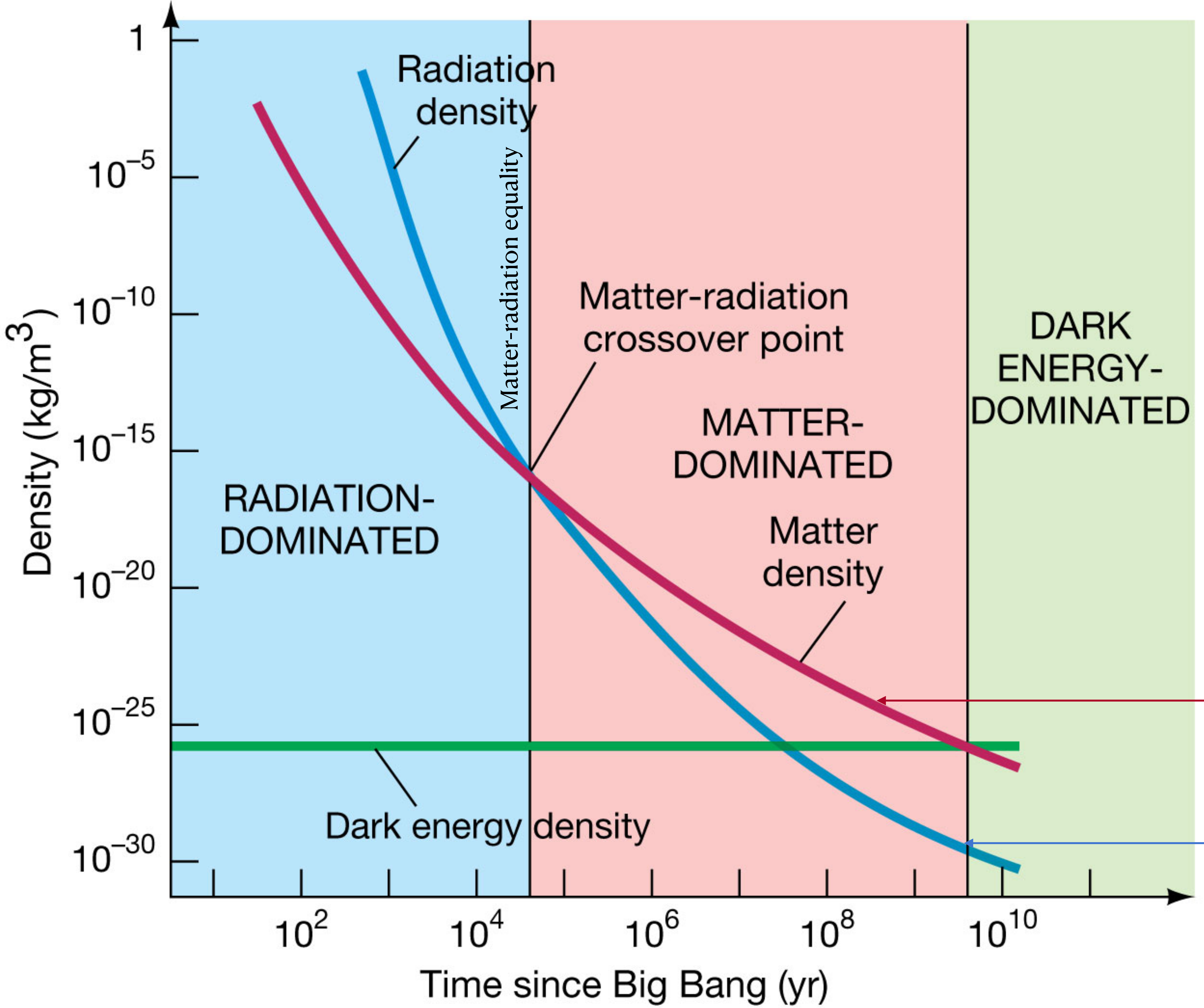
The energy density in radiation dilutes with the volume, but also stretches with space so that

$$\frac{\Delta\lambda}{\lambda} = z = \frac{1}{a} - 1$$

$$E = \frac{hc}{\lambda} \sim a^{-1} \sim T_r$$

Consequently, $\rho_r \sim a^{-4}$

and $T_r \sim a^{-1}$



Because of the different dependence on the expansion, there must have been a time in the past when the mass-energy in radiation exceeded that in matter.

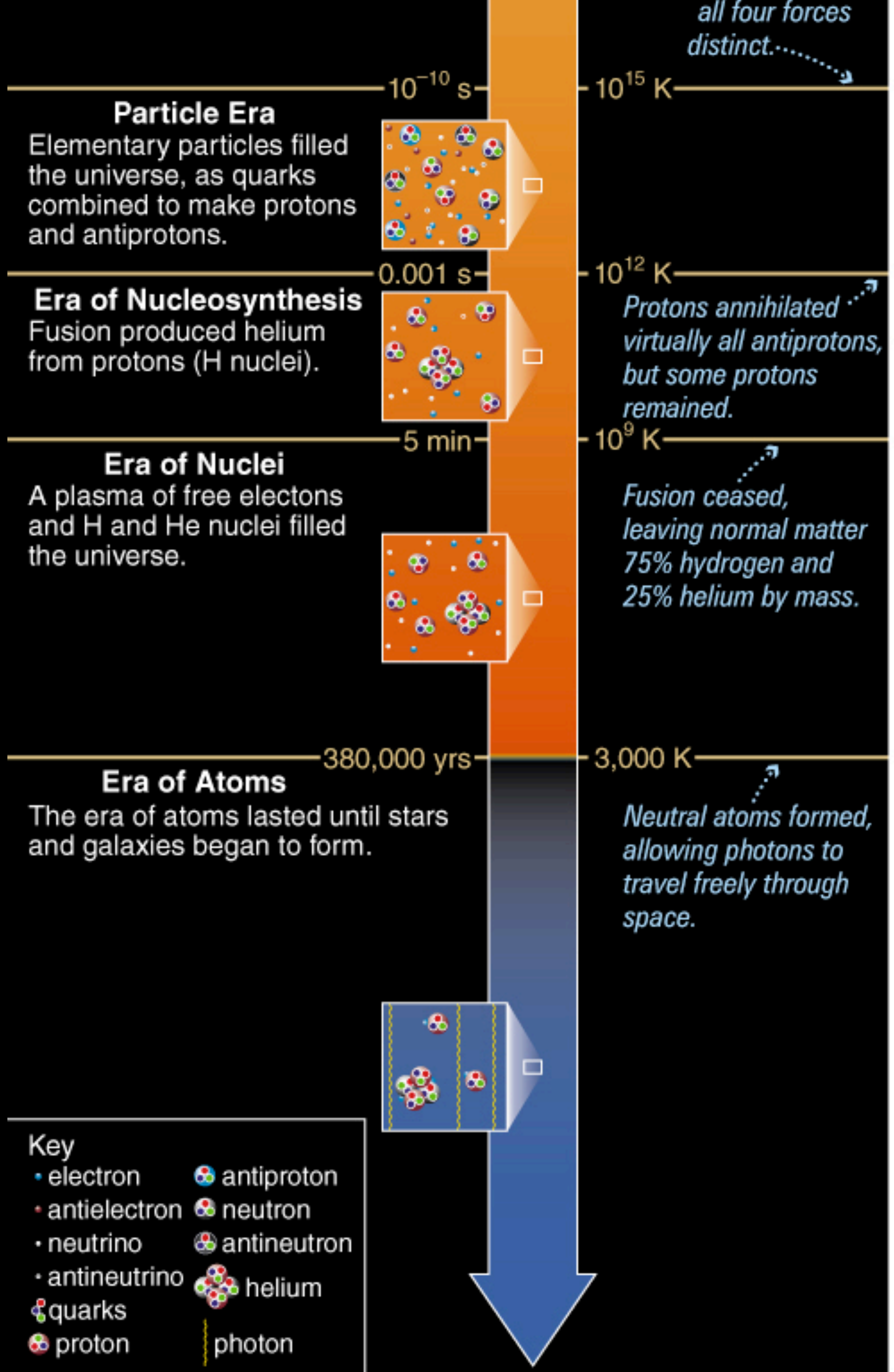
The redshift of matter-radiation equality occurred at

$$z_{\text{eq}} \approx 3{,}000$$

depending in detail on the current mass and radiation density.

$\rho_m \sim a^{-3}$

$\rho_r \sim a^{-4}$



particle soup

< millisecond

T ~ 10^{14} K

nucleosynthesis (BBN)

~ 3 minutes

T ~ 10^{10} K

Early Universe

recombination

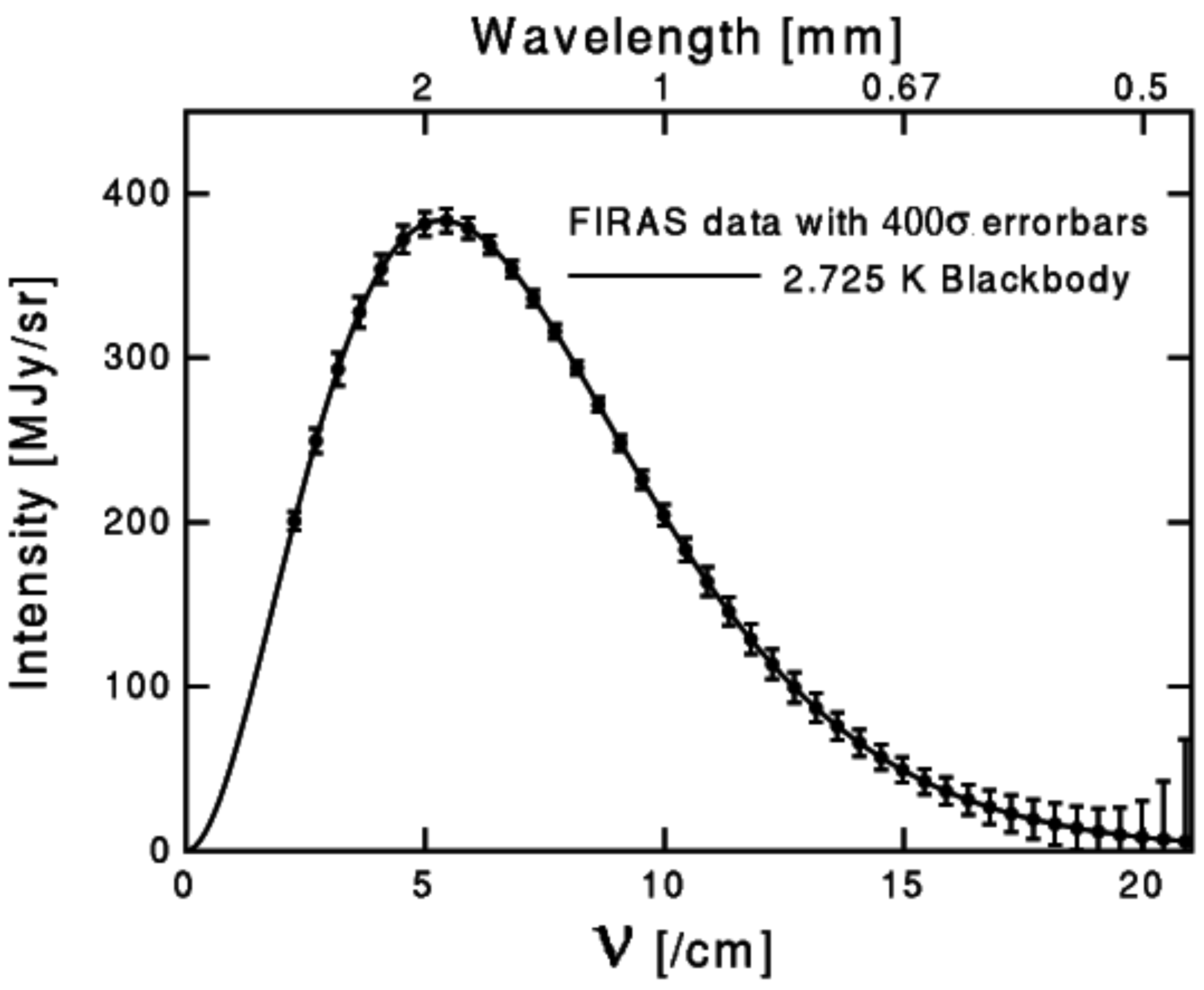
~380,000 year

T ~ 3000 K

emission of CMB:

surface of last scattering - transition from opaque plasma to transparent neutral gas

Cosmic Microwave Background

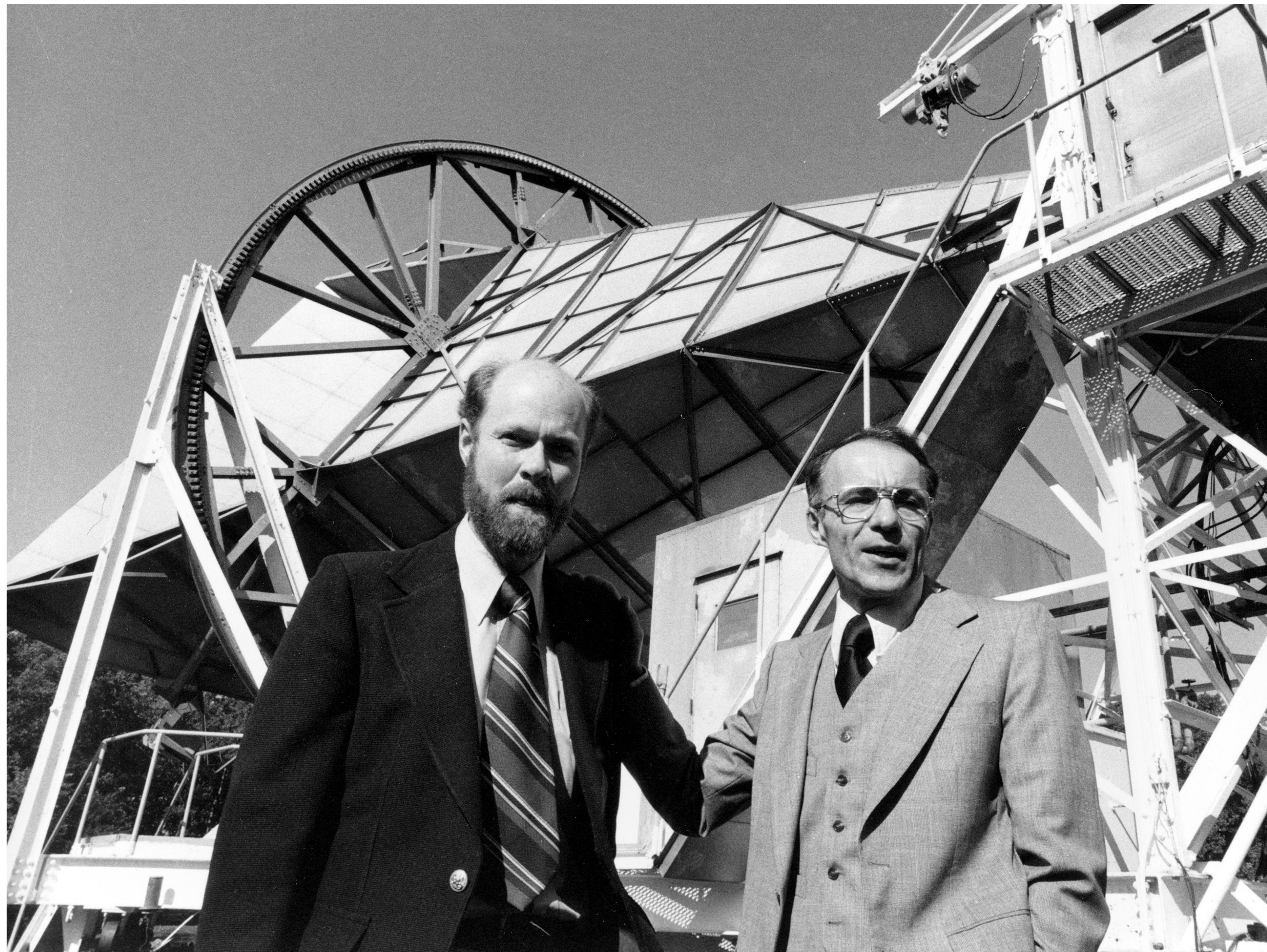


The Cosmic Microwave Background (CMB) is the relic radiation field of the Hot Big Bang. It has an essentially a perfect thermal spectrum with a current temperature of 2.725 K.

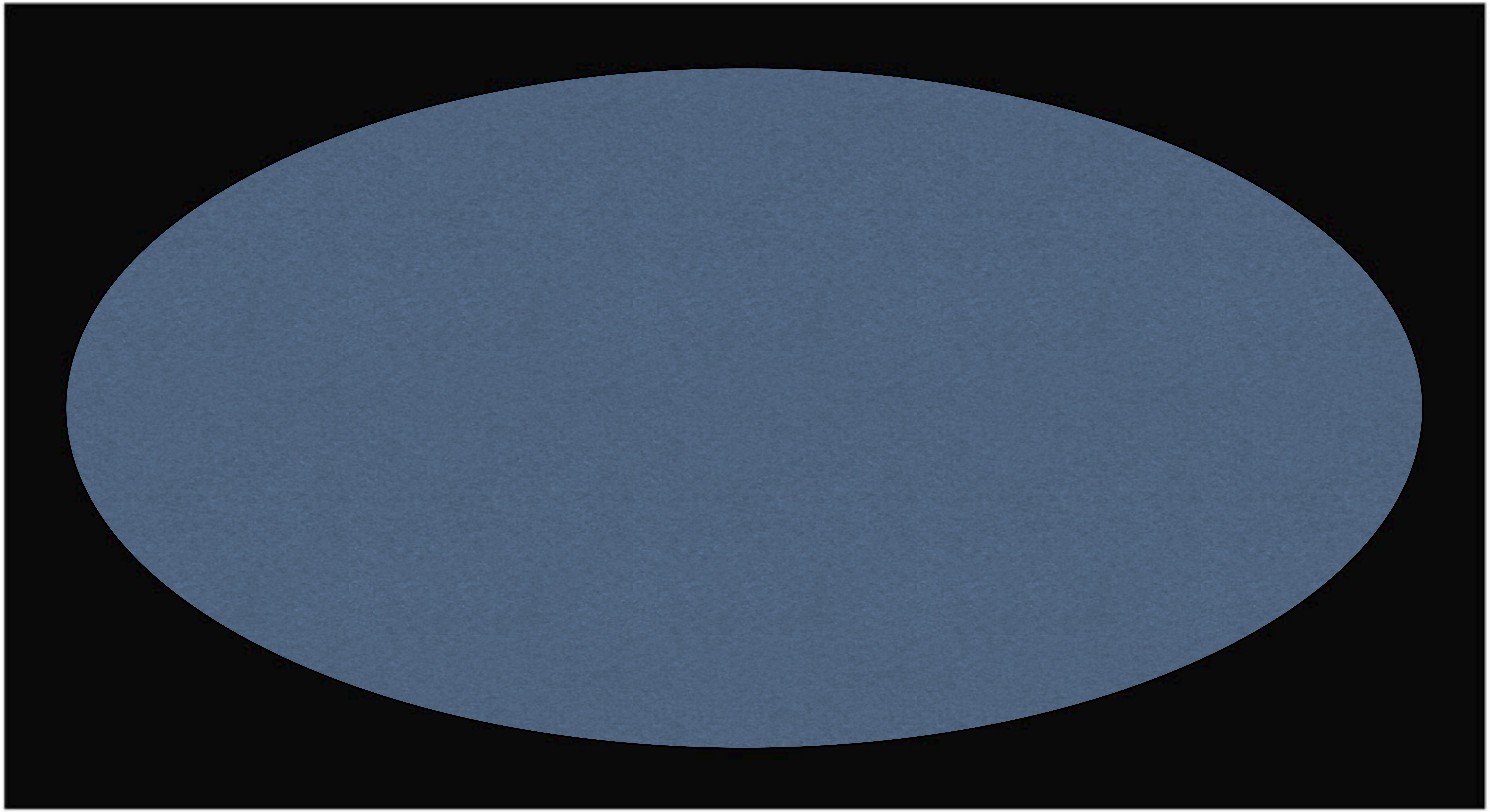
This was higher in the past by (1+z), so T ~ 3,000 K at the epoch of recombination. This is the point at which the high-energy tail of the blackbody distribution no longer had enough photons in excess of 1 Rydberg to keep the universe ionized.

The existence of the CMB had been anticipated by Gamow in the '50s, but this was largely forgotten by the '60s. It's predicted existence we rediscovered by Dicke & Peebles, who were actively searching for it when it was accidentally found by Penzias & Wilson.

Penzias & Wilson with the horn they discovered the CMB with at AT&T Bell Labs

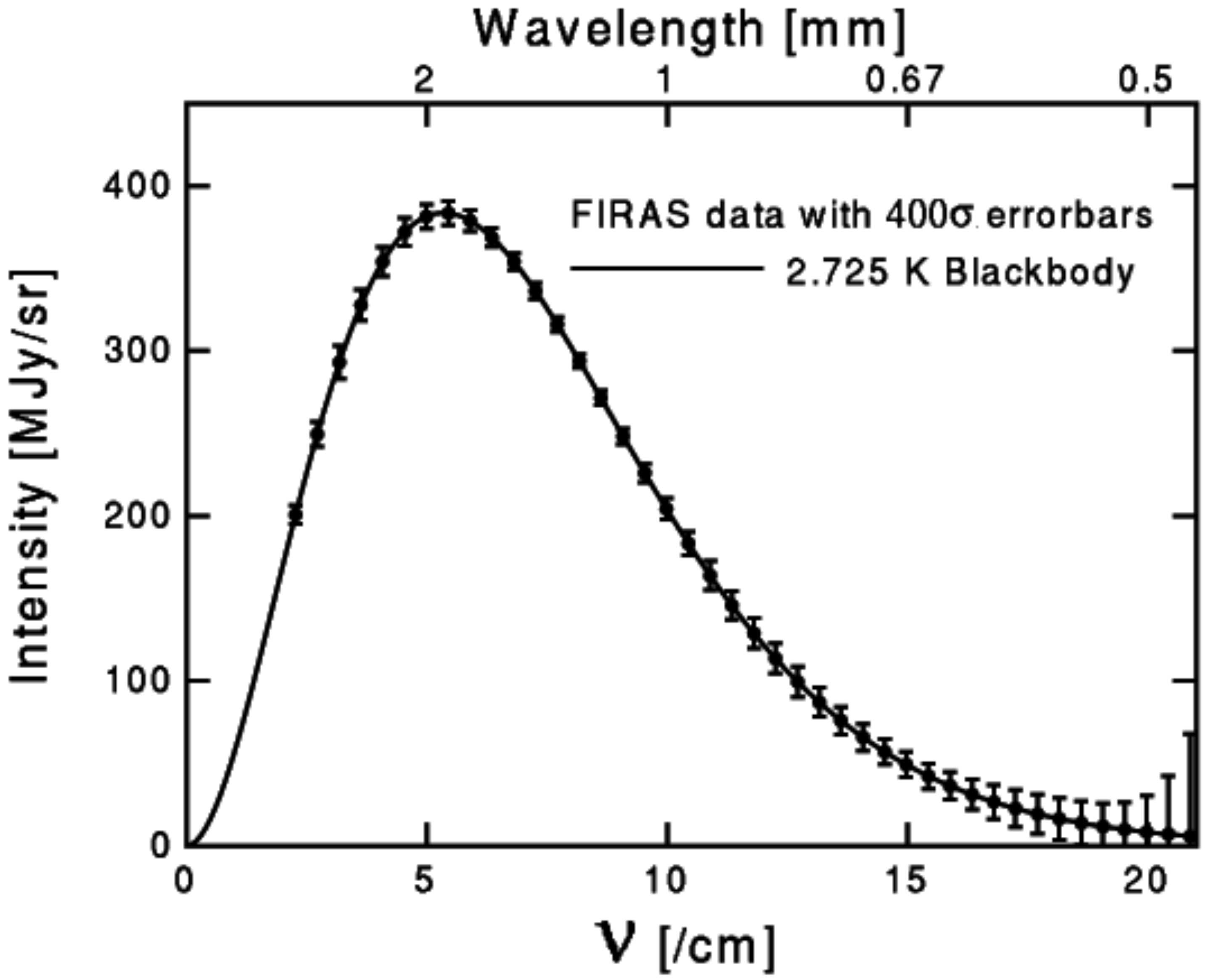


CMB: Baby picture of the universe (380,000 years old)



Same temperature everywhere on the sky to 1 part in 10^5

Cosmic Microwave Background



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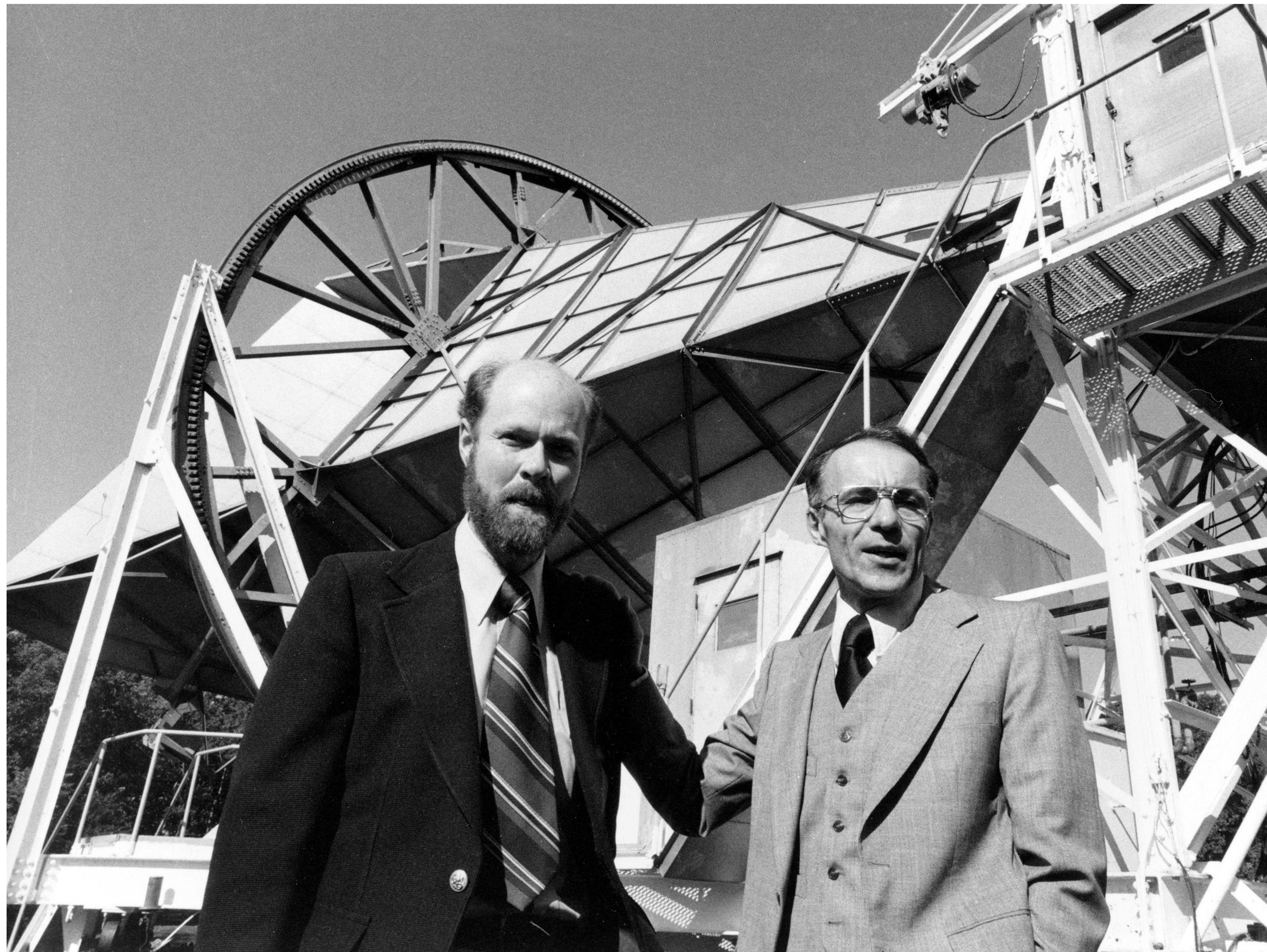
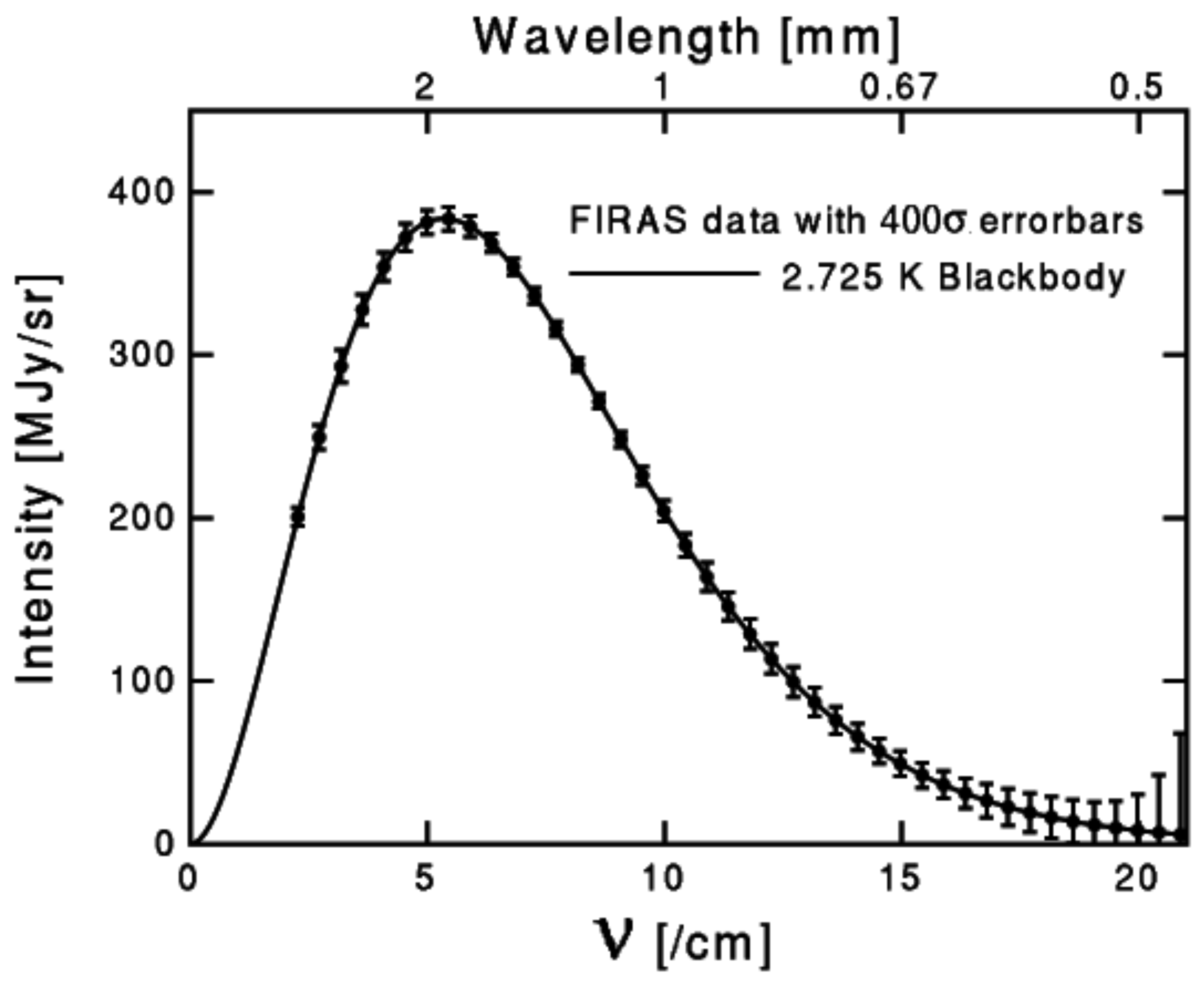


Cosmic Microwave Background



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Current temperature $T_0 = 2.725 \text{ K}$

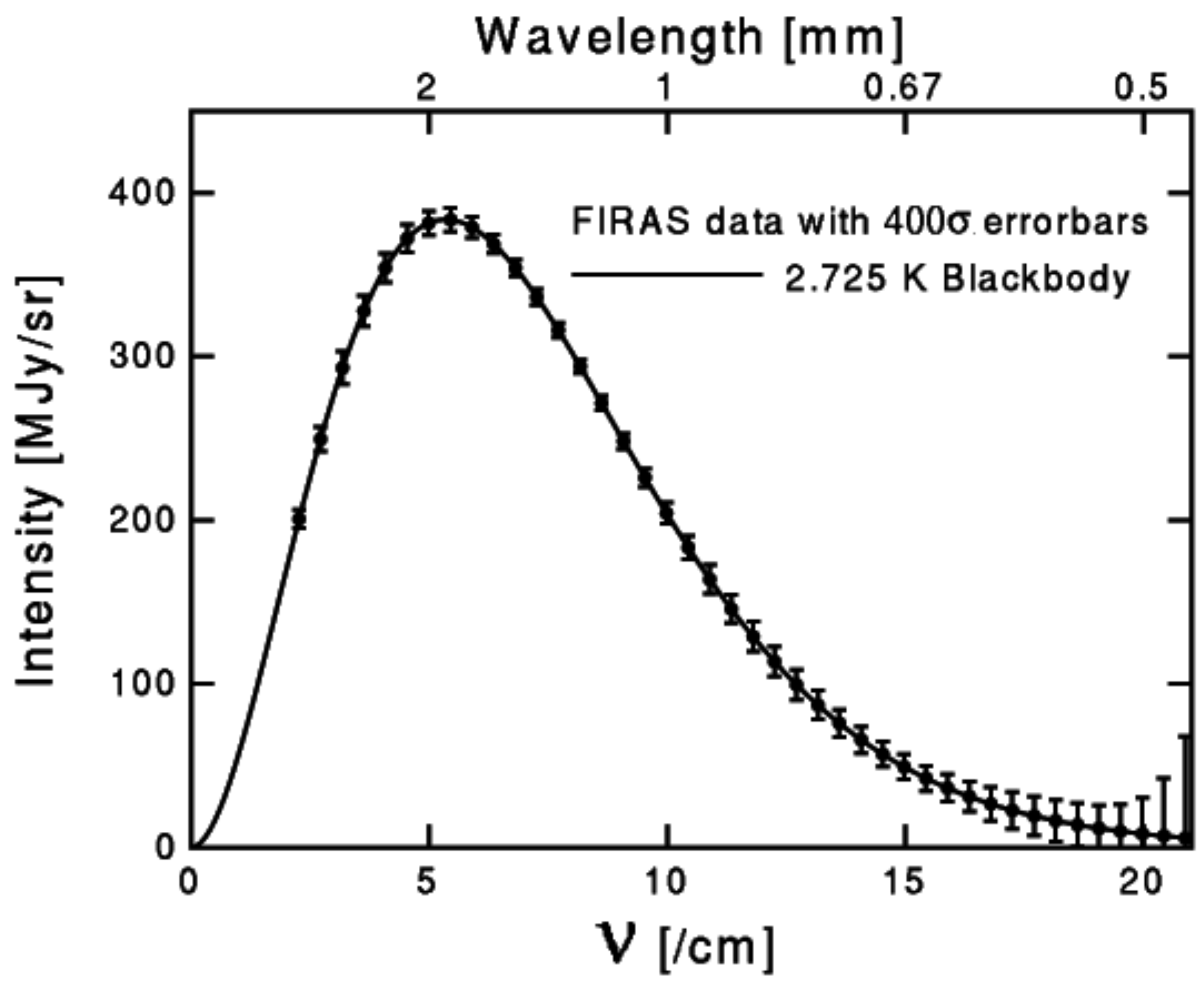
Energy density $\varepsilon_0 = \alpha T_0^4 = 0.261 \text{ MeV m}^{-3}$

α is the radiation density constant

Relative to the critical density $\Omega_r = 5 \times 10^{-5}$

Number density of photons $n_{\gamma,0} = 4.11 \times 10^8 \text{ m}^{-3}$

This greatly exceeds all the photons produced by all the stars throughout the universe over all time.



We observe the CMB as the "surface of last scattering" that occurs at the epoch of recombination. This is the point at which the early universe transitions from an opaque plasma of protons and electrons to a mostly transparent neutral gas of hydrogen and helium.

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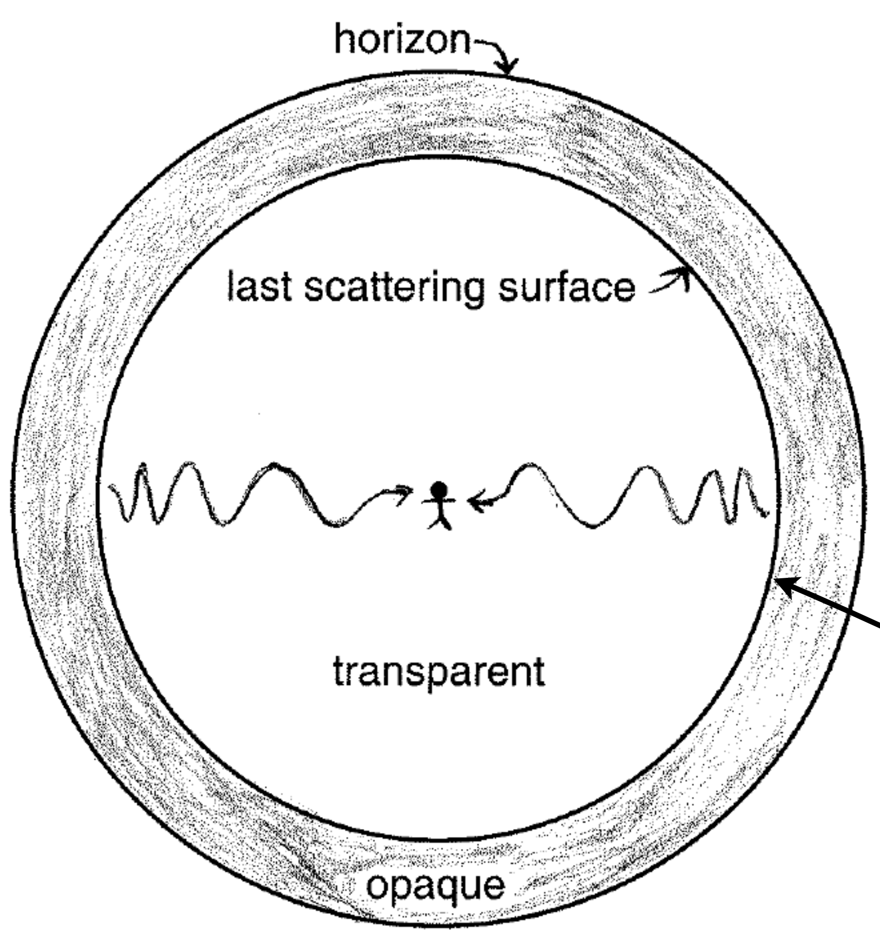
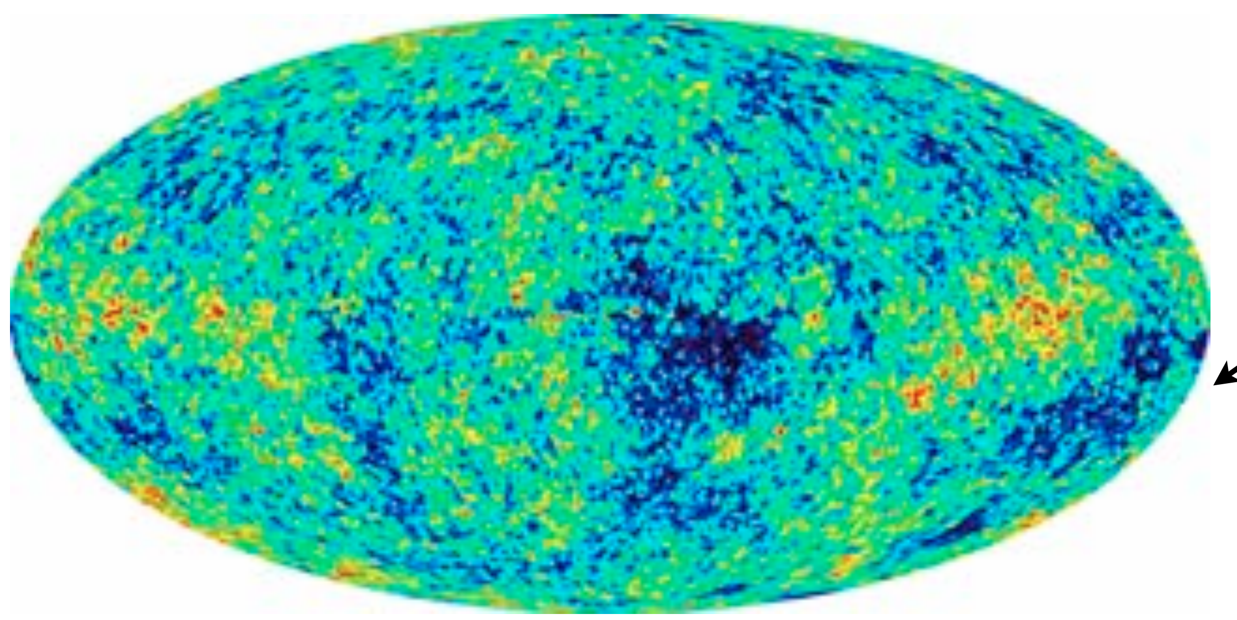


Figure 9.3: An observer is surrounded by a spherical last scattering surface. The photons of the CMB travel straight to us from the last scattering surface, being continuously redshifted.



This full-sky image from WMAP is the surface of last scattering