

# Phys 321: Lecture 11

## The Big Bang Theory



SUWALLS

# Phil Plait's Crash Course

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$$-\frac{8}{3}\pi G\rho$$

$$\frac{1}{3}\Lambda c^2 - \frac{kc^2}{R^2}$$

$$\left(\frac{\dot{R}}{R}\right)^2$$

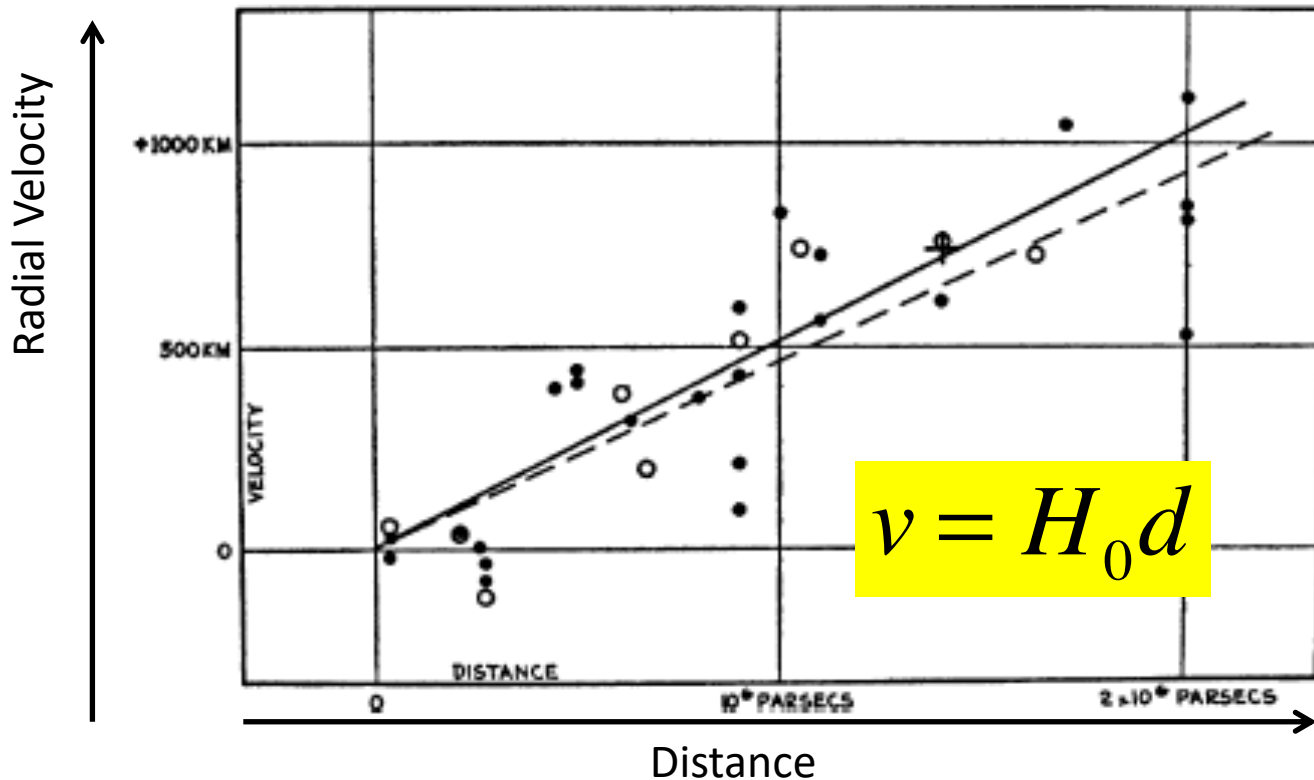
*COSMOLOGY PART 1*

# ***THE BIG BANG***

# The Big Bang Theory

- The prevailing cosmological model for the Universe
- Main evidence
  - The Hubble's Law
  - The cosmic microwave background radiation (CMB)
  - The abundance of light elements

# Hubble's Law and the Expansion of Space



Can be explained by **expansion of space** + **cosmological principle**: the Universe is **homogeneous** and **isotropic** on a large enough scale



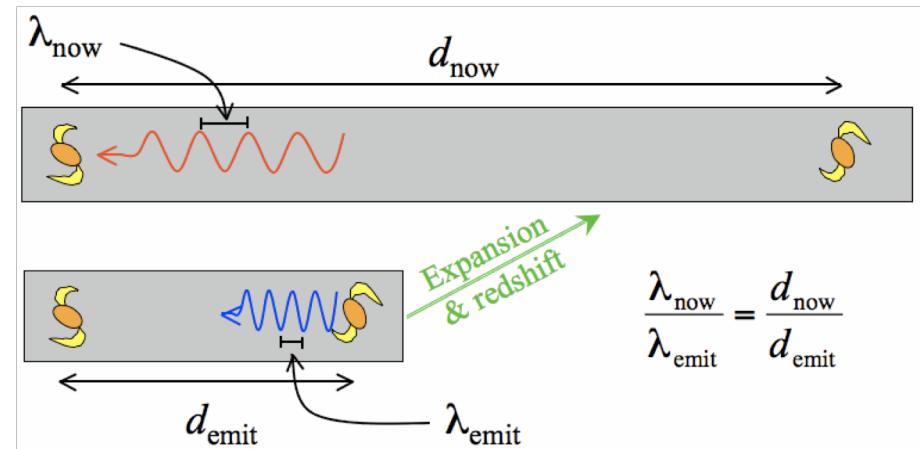
# Cosmological Redshift

- Cosmological Redshift results from the expansion of space itself

Let  $R$  be the scaling factor of the space when the light is emitted, with  $R_0 = 1$  at present day  $t_0$

$$Z = \frac{\lambda_0 - \lambda}{\lambda} = \frac{R_0 - R}{R}$$

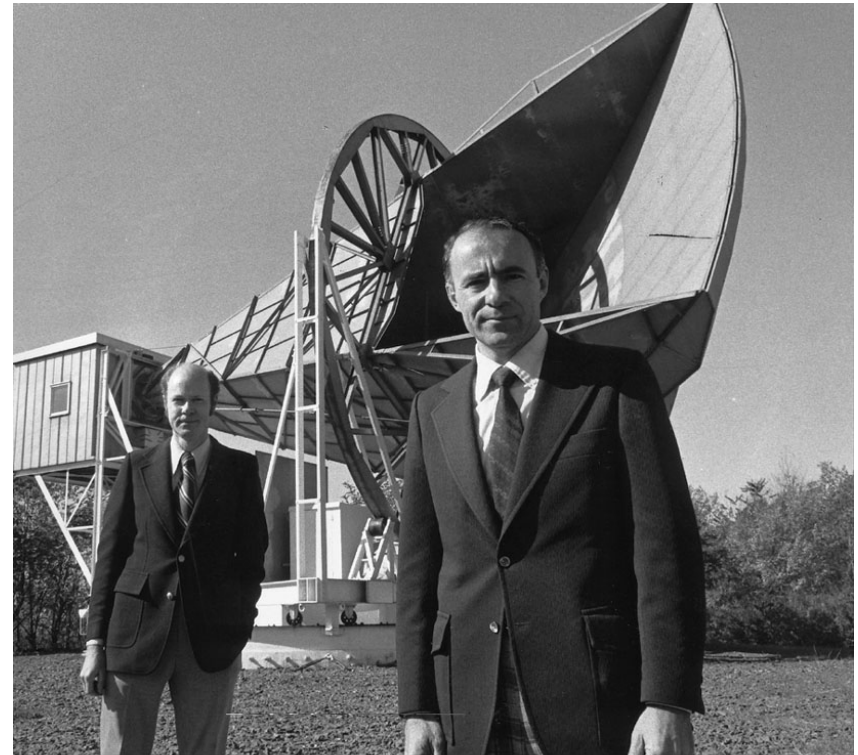
$$R = R_0 / (1 + z) = 1 / (1 + z)$$



E.g., Looking back at galaxies at  $z = 6$ , the space is 7 times closer

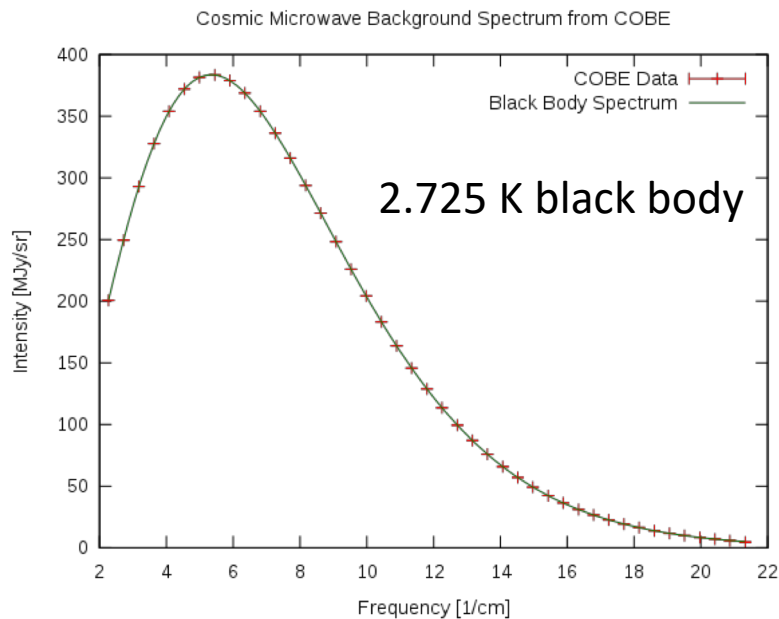
# The cosmic microwave background

- In 1948, Ralph Alpher and Robert Herman predicted a “leftover heat” of the big bang has a blackbody temperature of  $\sim 5$  K.
- Due to the expansion of the space as well as redshift of the light
- In 1964, Arno Penzias and Robert Wilson discovered a 3 K blackbody background in microwave wavelengths using the Holmdel Horn Antenna



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# The cosmic microwave background



CMB: The most-precisely measured black body spectrum in nature

- About 377,000 years after the big bang (redshift of  $z = 1100$ ), the universe cooled enough for lots of protons and electrons combined to form neutral atoms ( $\sim 3,000$  K – recall the Saha Equation)
- At that moment the Universe becomes transparent (optically thin)
- Photons decouple from matter and stream freely in space. They come off *the surface of last scattering*
- When we receive the photons today, they become highly redshifted, resulting in the much cooler 2.725 K blackbody radiation—the CMB

# The CMB: A derivation

Let  $R$  be the scaling factor of the (expanding) space, with  $R_0 = 1$  at present day

Recall energy density of radiation field is  $u = aT^4$

Energy conservation says  $uV = u_0V_0$

Which gives  $R^3 aT^4 = aT_0^4$

However, the energy of each photon we receive is **redshifted**:

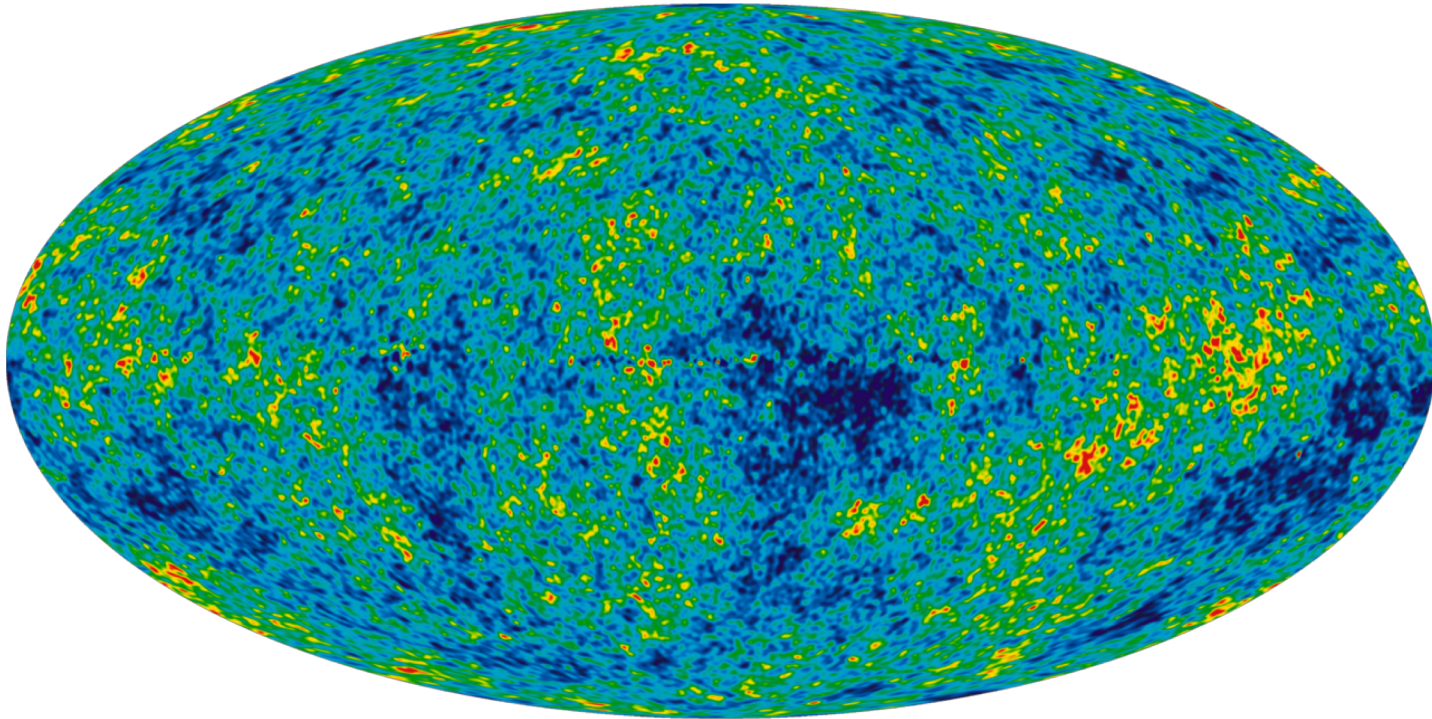
$$(\lambda_0 - \lambda) / \lambda = (R_0 - R) / R = z \quad \text{or} \quad R = R_0 / (1 + z) = 1 / (1 + z)$$

A photon with  $\lambda_0$  at present time has a wavelength  $\lambda = R\lambda_0$  at other times. So we need another factor of  $R$  on the left

$$R^4 aT^4 = aT_0^4 \quad \text{so} \quad T_0 = RT = T / (1 + z)$$

$T = 3,000$  K when the universe becomes transparent,  $z = 1,100$

# All-sky CMB Observations



- CMB observations tell us the cosmological principle is correct: the Universe is highly isotropic.
- The figure above shows anisotropies of the CMB at  $1/100,000$  level, possibly generated by tiny quantum fluctuations of matter during the earlier expansion of the universe

# Big Bang Nucleosynthesis

- Between about 3-20 minutes after the Big Bang, the temperature and pressure of the universe allow **nuclear fusion** to occur
- Big Bang produces about 1 neutron for every 7 protons
- Nucleosynthesis results in 75% hydrogen and 25% helium by mass, which is the amount we find today from old galaxies!



