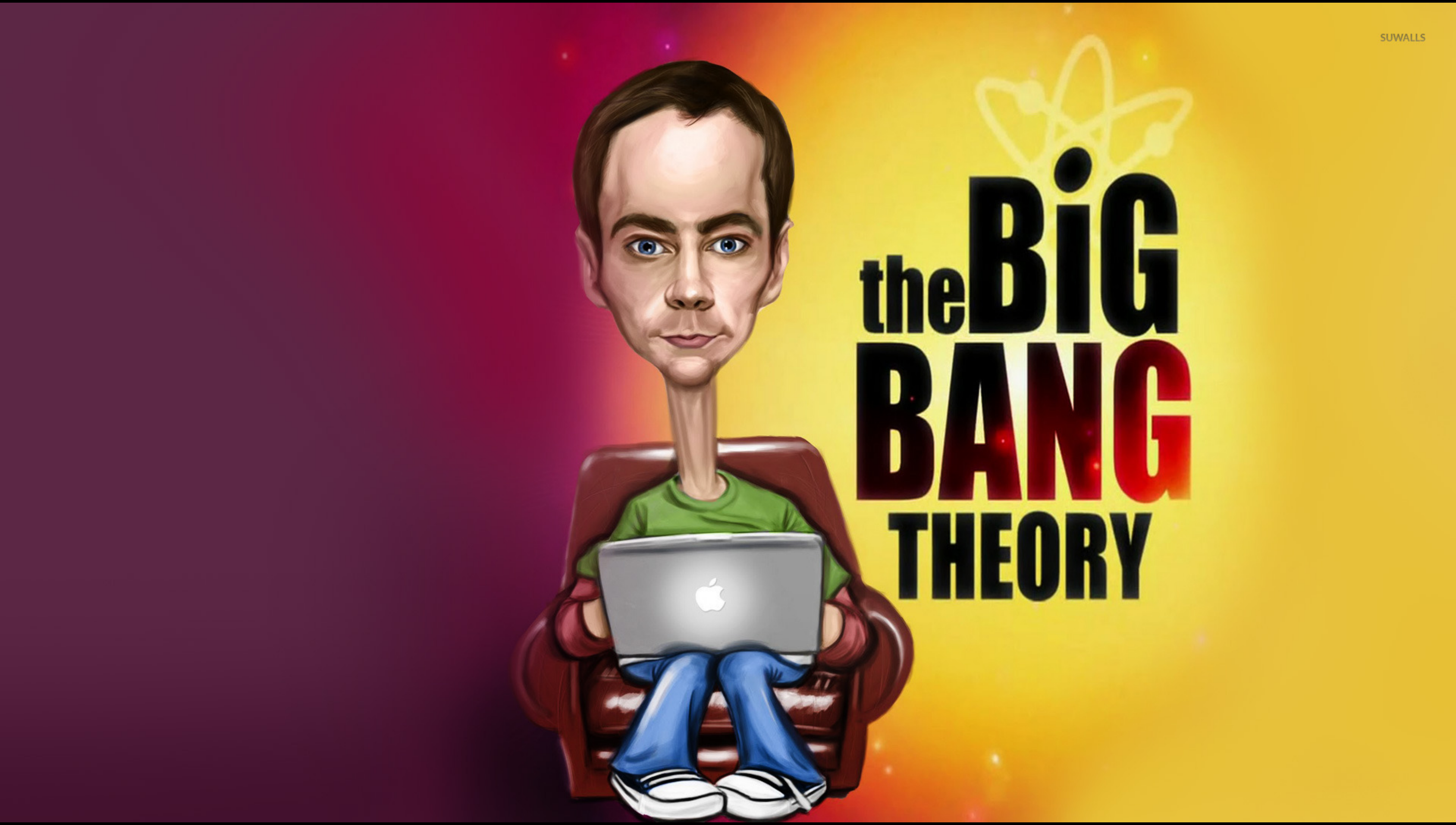
# Phys 321: Lecture 13
# The Big Bang Theory

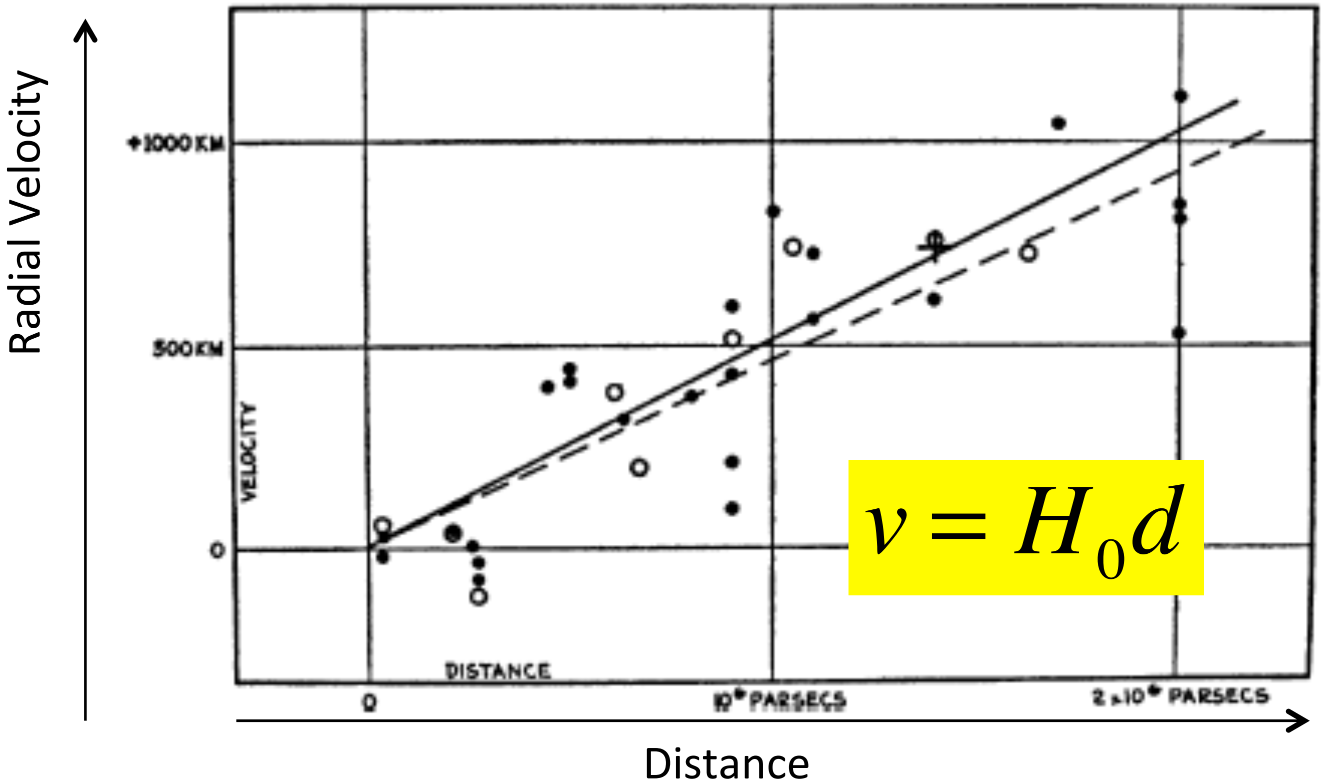



Prof. Bin Chen, Tiernan Hall 101, bin.chen@njit.edu

# 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

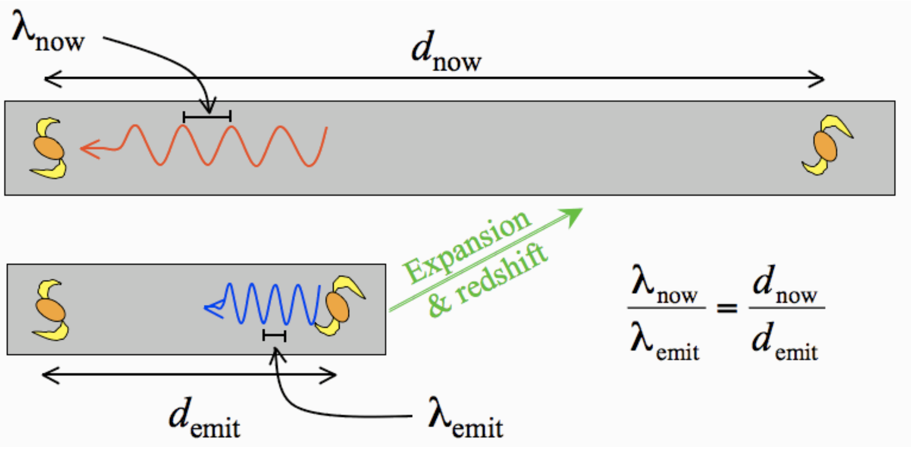



$$v = H_0 d$$

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 $t_0$

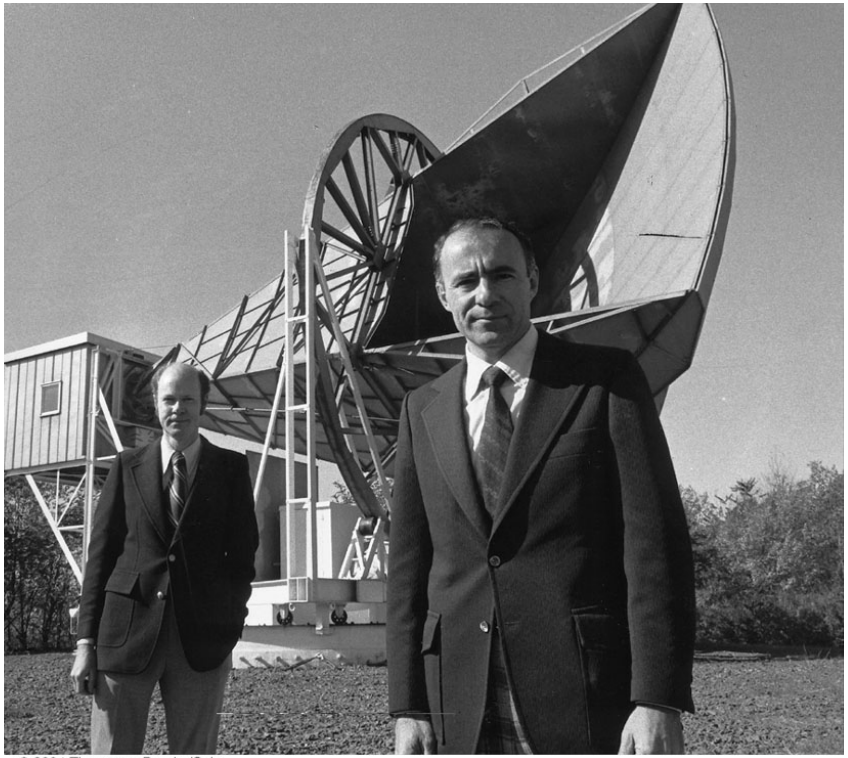
$$Z = \frac{\lambda_0 - \lambda}{\lambda} = \frac{R_0 - R}{R}$$

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

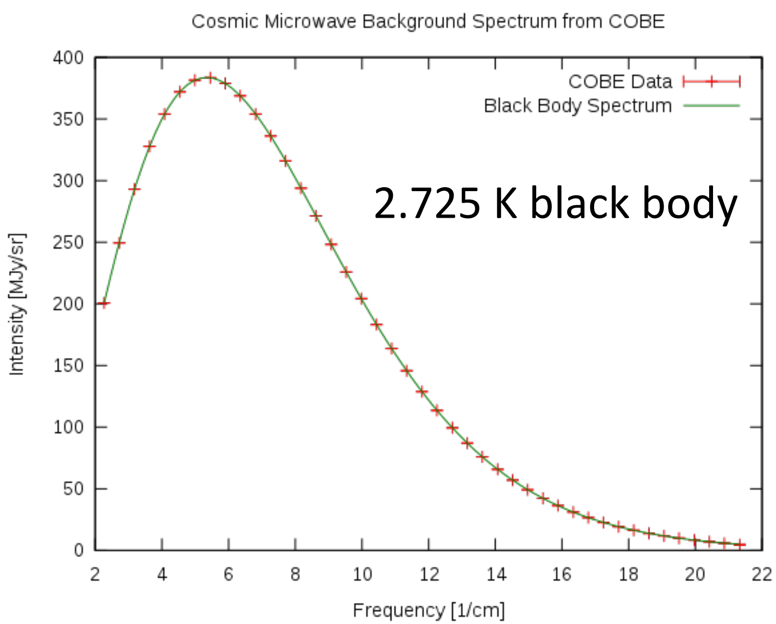
E.g., Looking back at galaxies at z = 6, the space is 7 times closer

# The cosmic microwave background

- In 1948, Ralph Alpher and Robert Herman predicted a “leftover heat” of the big bang has a blackbody temperature of ~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



# 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 (~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 $uV = u_0 V_0$

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

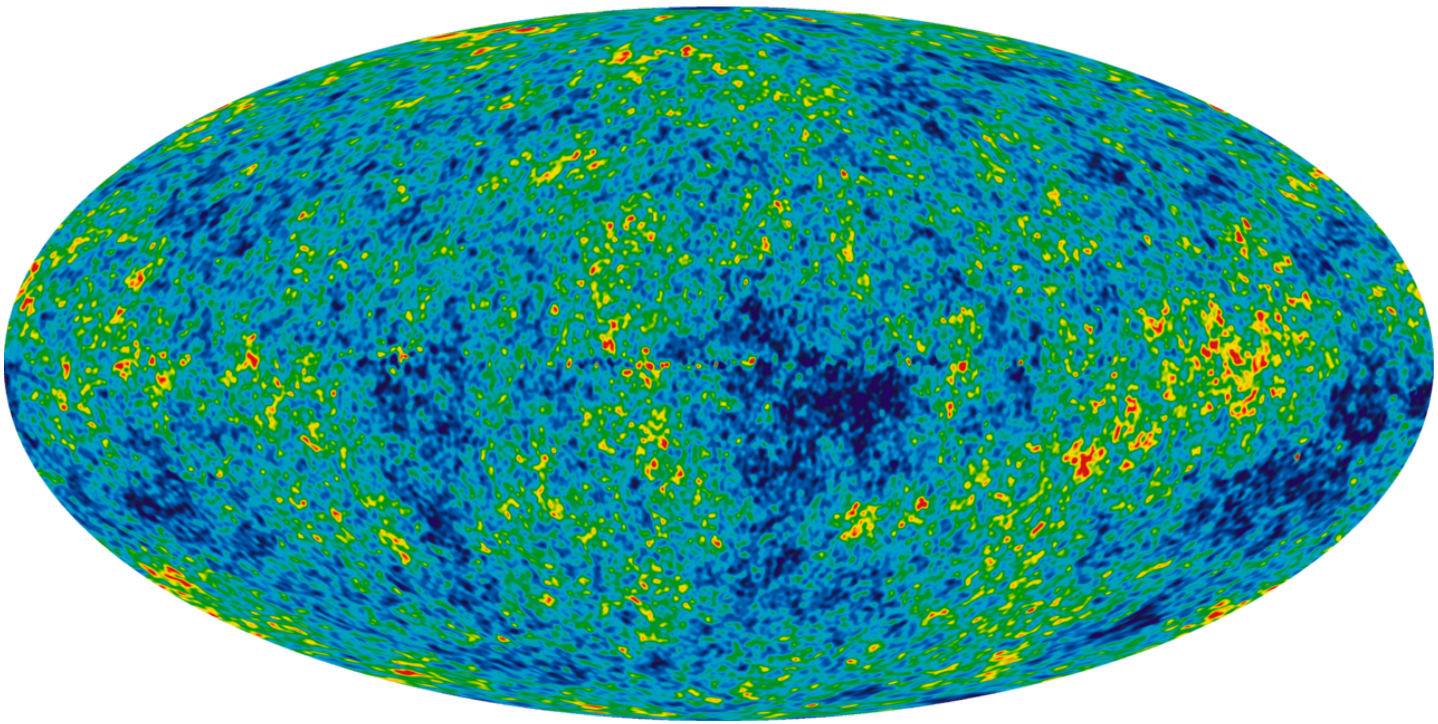
However, the energy of each photon we receive is redshifted:

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

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

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

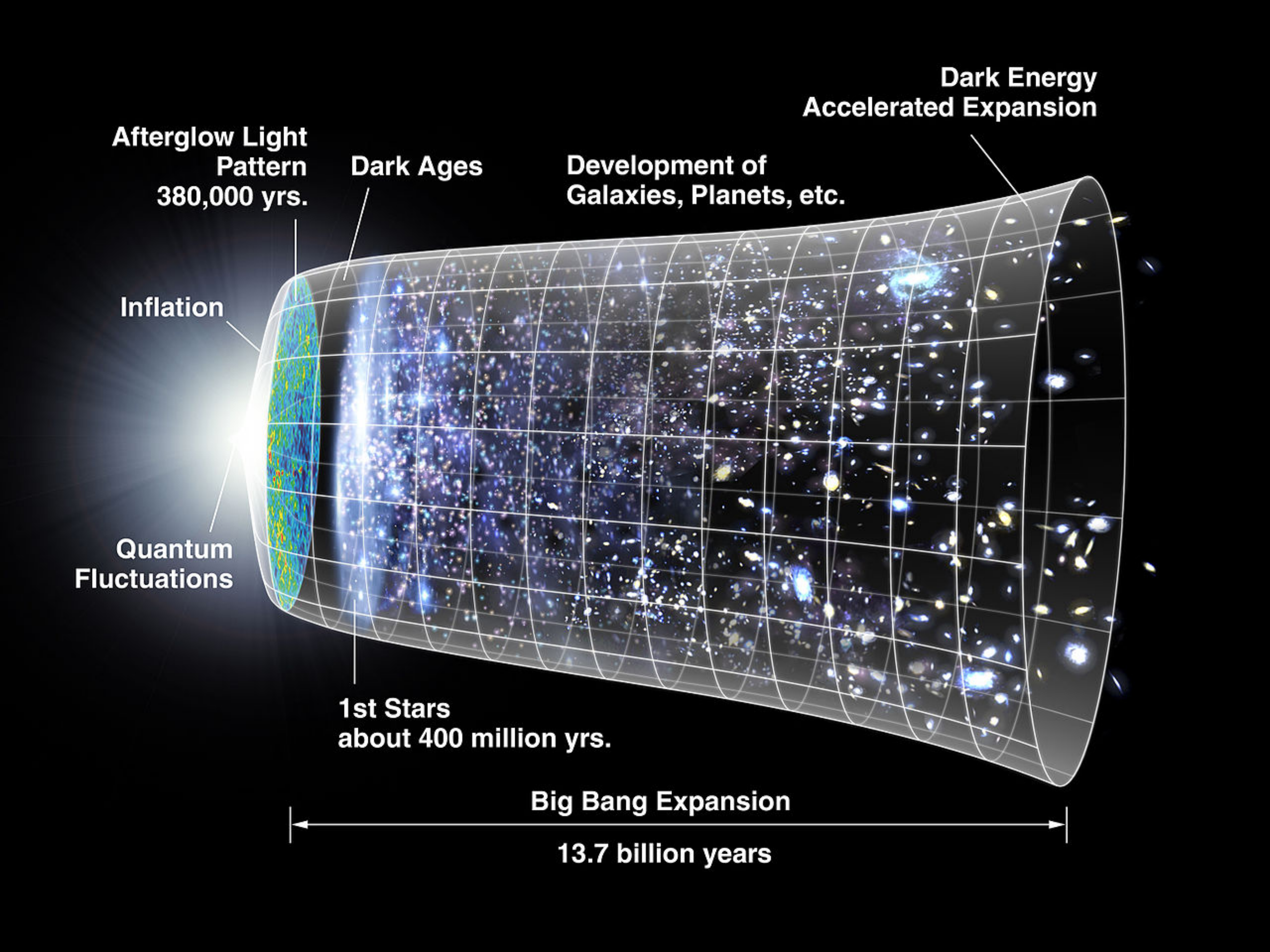
# All-sky CME Observations



- 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!


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years