Outline: Evidence for Big Bang theory

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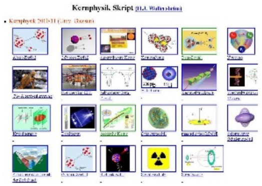
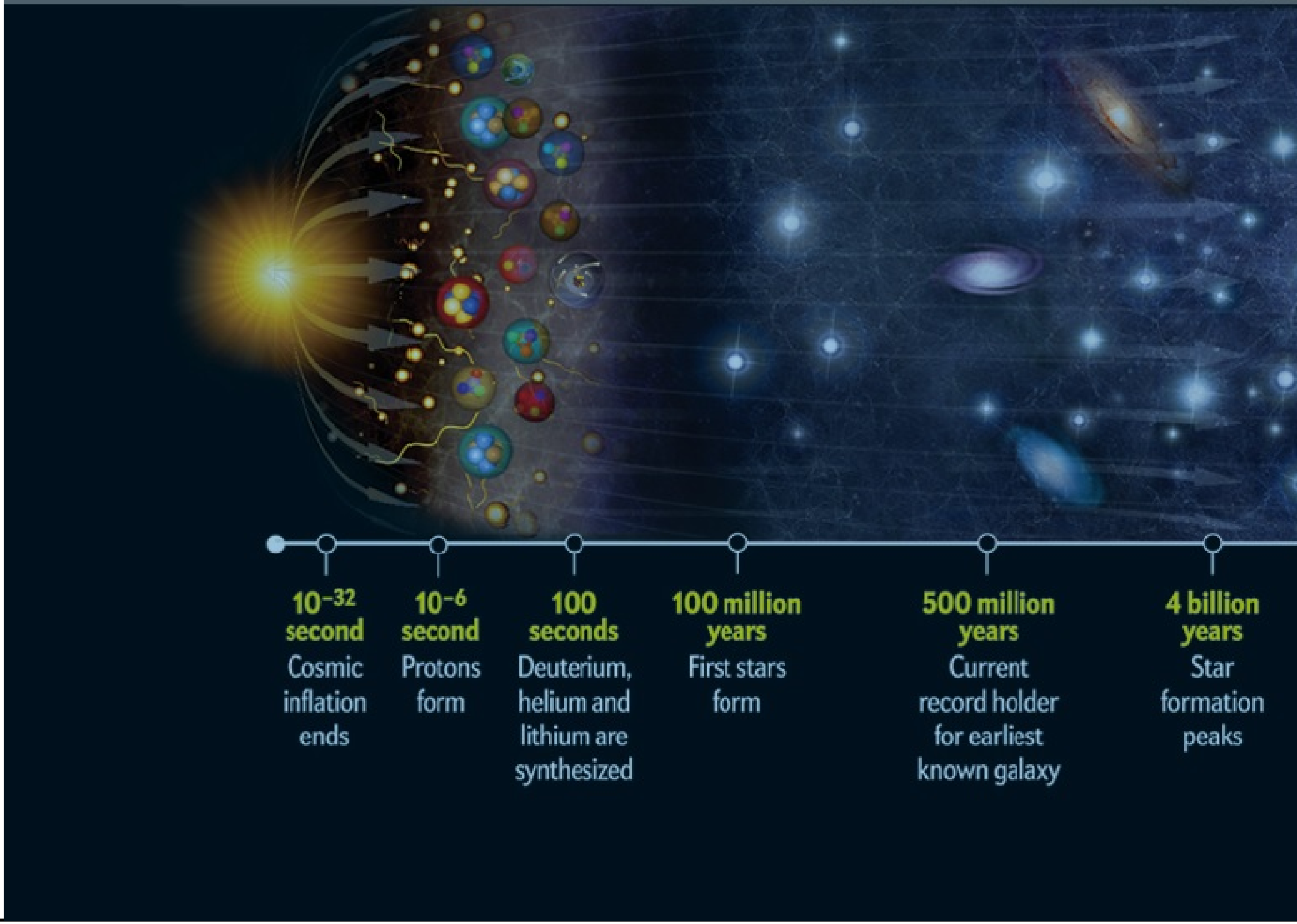
web-page: https://web-docs.gsi.de/~wolle/ and click on



1. 3 pillars of Big Bang theory
2. Hubble expansion
3. nucleosynthesis
4. cosmic microwave background radiation

The first 3 minutes Steven Weinberg

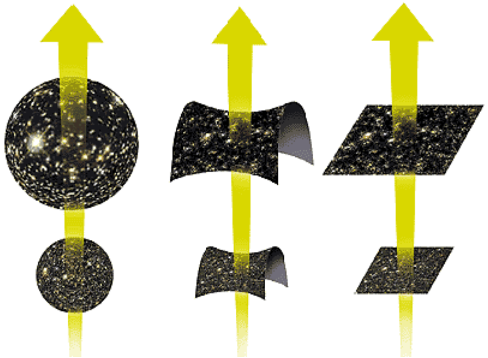


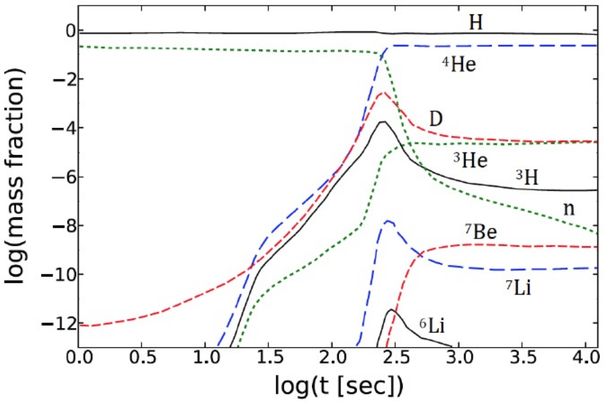
Big Bang: Main steps

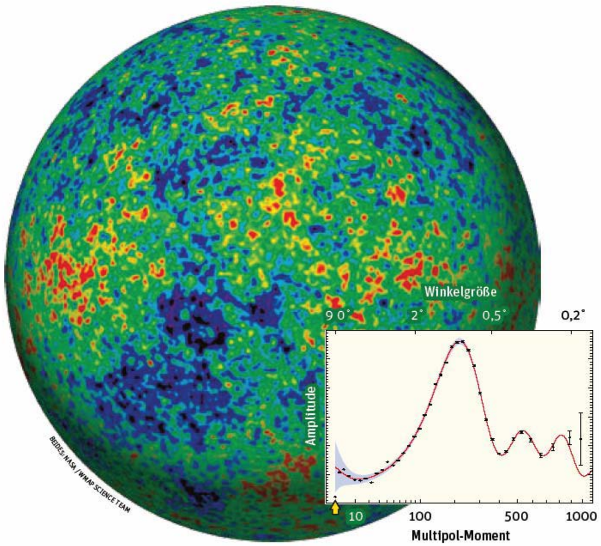
1) Universe started ~15 Ga, the size of an atom, at temperatures (or energy) too hot for normal matter > 10^{27} K – it start expanding extremely rapidly
2) Within 10^{-32} seconds, it cools enough to form a quark soup + electrons and other particles
3) At about 1 second, the universe was a hot and dense mixture of free electrons, protons, neutrons, neutrinos and photons.
4) At about 13.8 seconds, temperature has decreased to 3 x 10^{9} K and atomic nuclei began to form, but not beyond H and He. The universe was a rapidly expanding fireball!
5) 700 000 years later electrons became attached to nuclei of H and He – formation of true atoms. Matter became organized into stars, galaxies and clusters

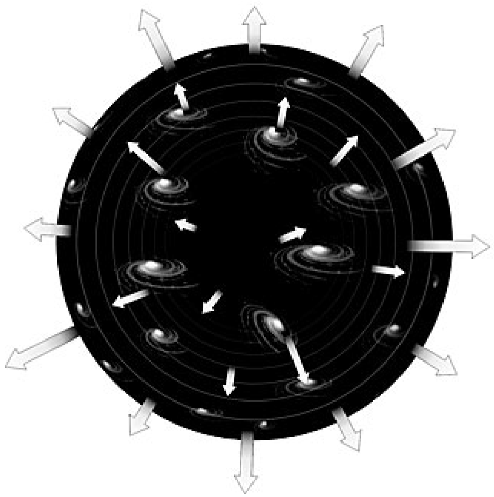
“Three Pillars” of Big Bang Theory

Hubble Expansion – Nucleosynthesis – 3 K Background Radiation

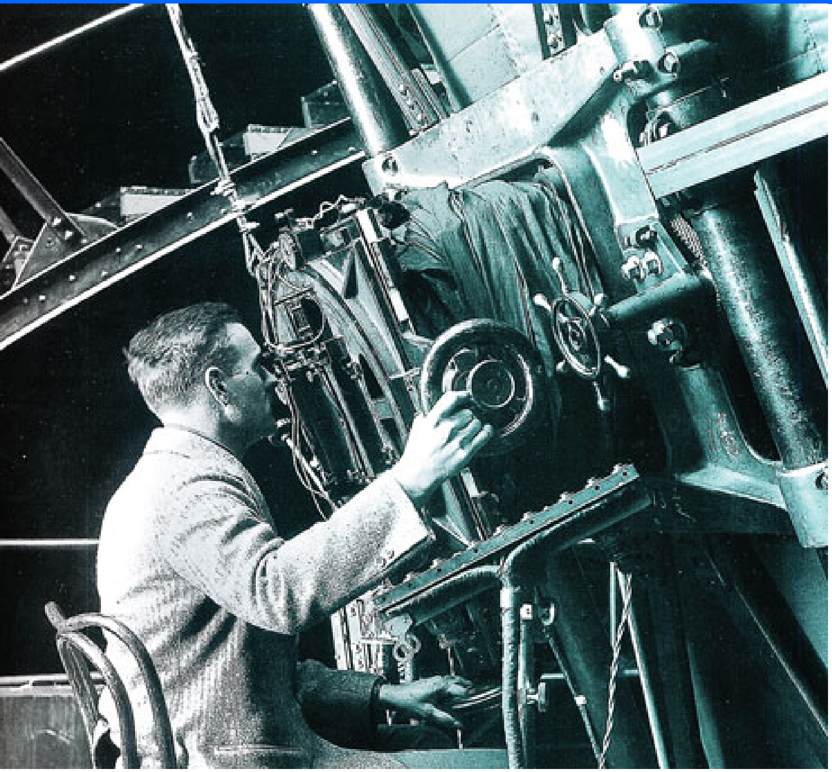


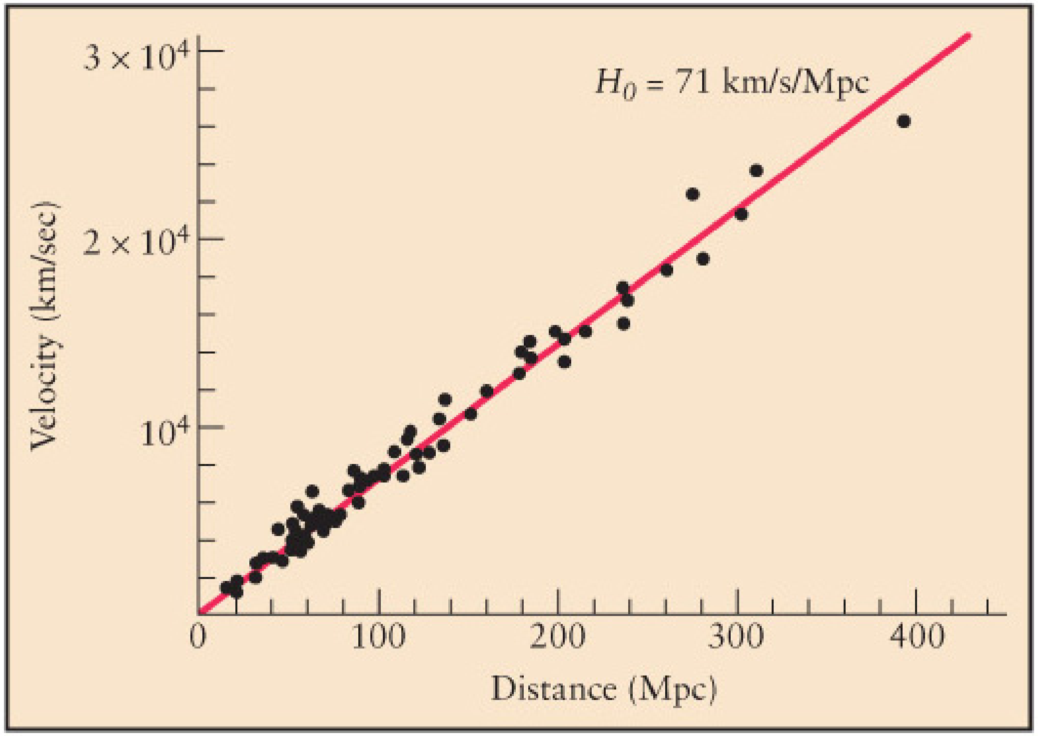






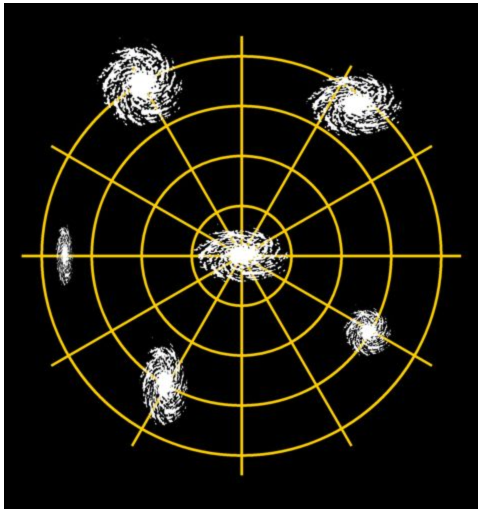
1. Edwin Hubble (1920): "Universe is expanding in all directions"



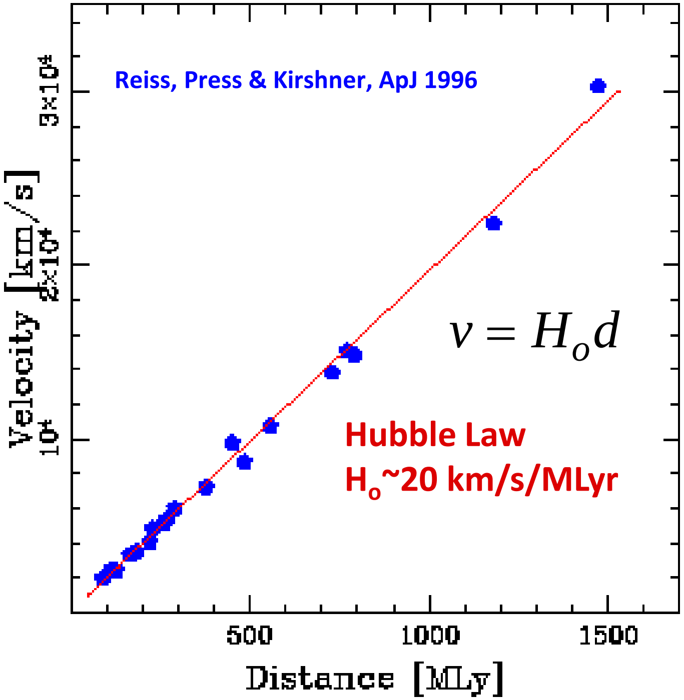


Age of the universe:

$$T = \frac{1}{H_0} = \frac{1\,s\,MLy}{20\,km} = \frac{10^6 \cdot 9.461 \cdot 10^{12}\ s\,km}{20\,km} = 15 \cdot 10^9\ y$$



SNe Ia Hubble Diagram



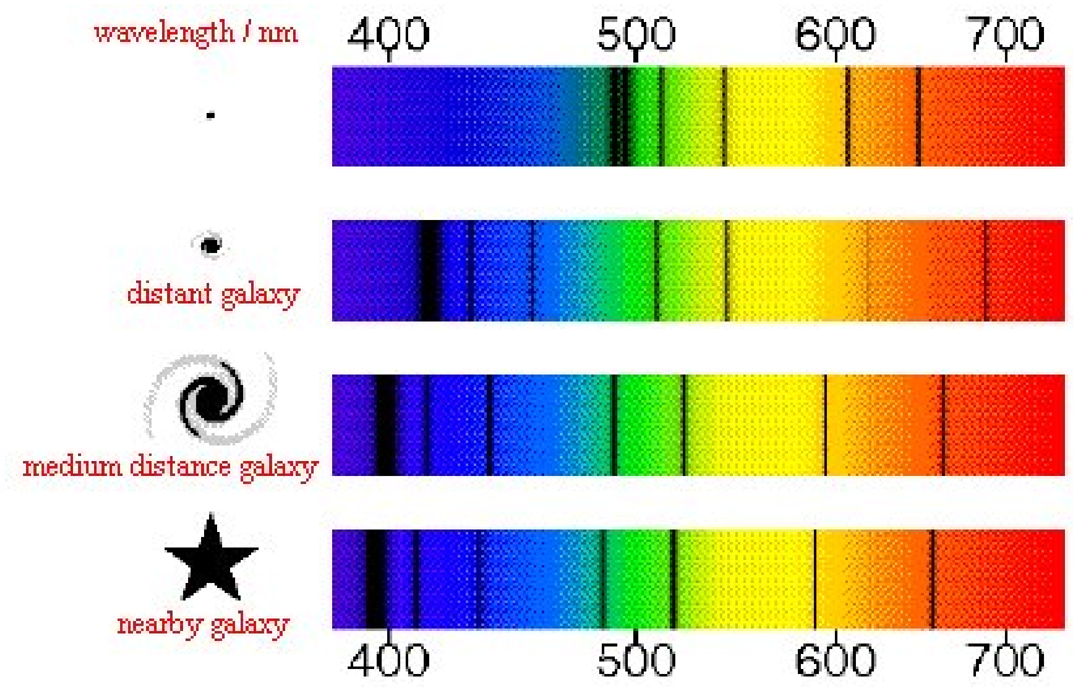
$$1\,pc = \frac{1.5 \cdot 10^{11}\ m}{4.85 \cdot 10^{-6}} = 3.086 \cdot 10^{16}\ m = 3.26\,Ly$$

Speed of stars or galaxies - Redshift

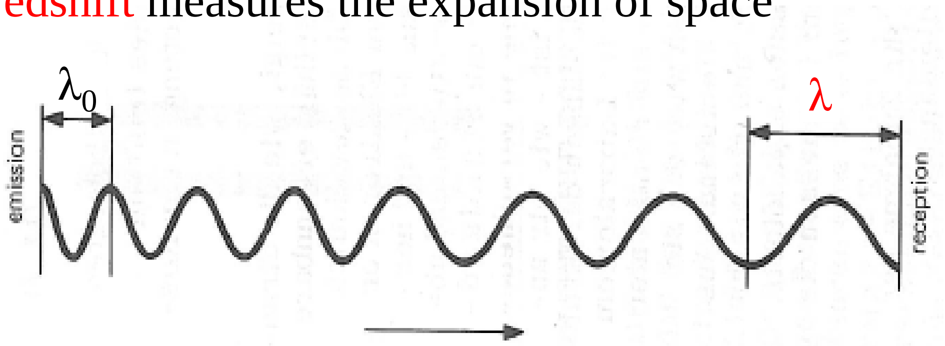
Doppler effect:

- if stars are approaching
  shorter wave length

- if stars are receding
  large wave length



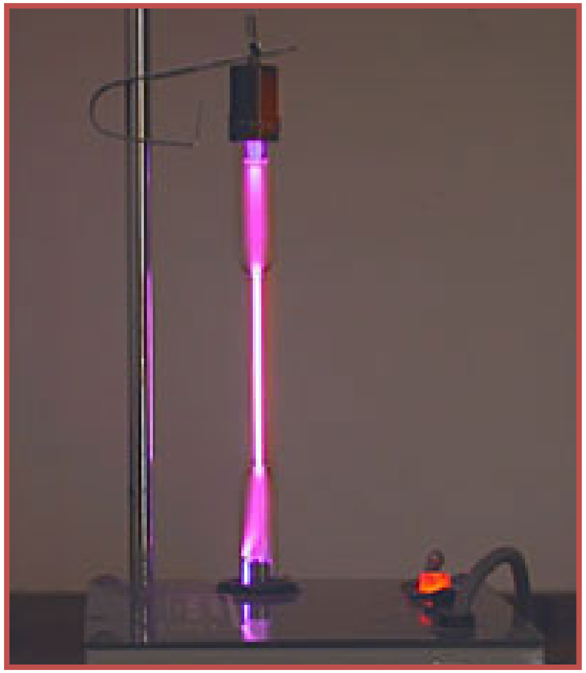
Cosmological redshift measures the expansion of space



$$z = \frac{\lambda - \lambda_0}{\lambda} = \sqrt{\frac{c+v}{c-v}} - 1$$

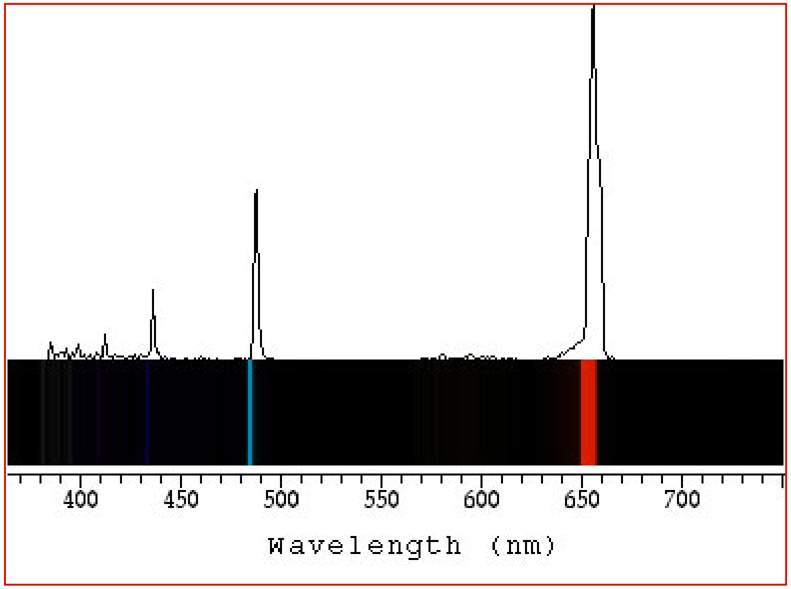
$$z = 6.68 \quad \Rightarrow \quad v \approx 58/60 \cdot c$$

Expanding Universe



Hydrogen lamp

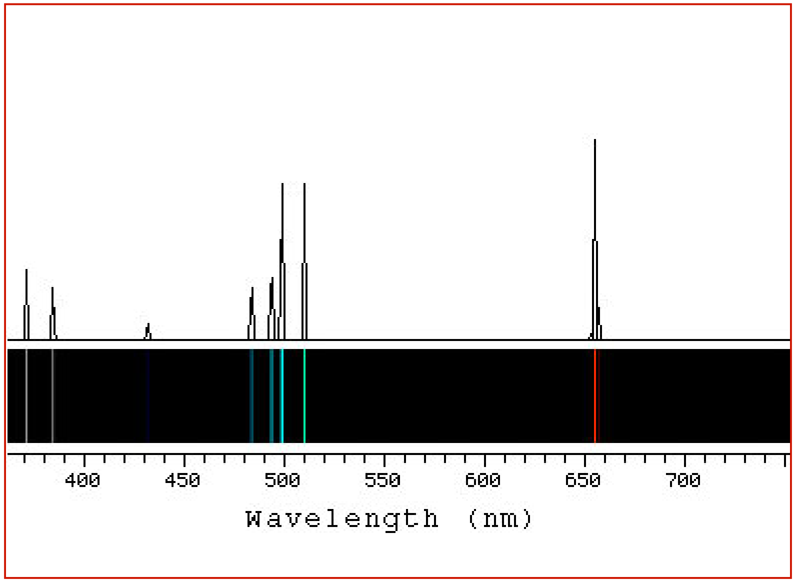
Spectrum of Hydrogen gas is a unique finger print of the element



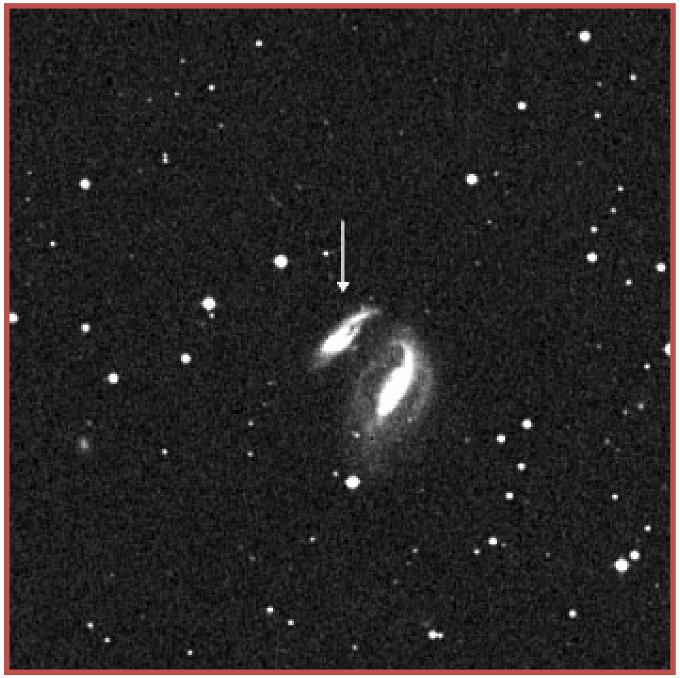
Expanding Universe

Orion Nebula

If one observes the same spectrum as in the laboratory, Hydrogen should be present.

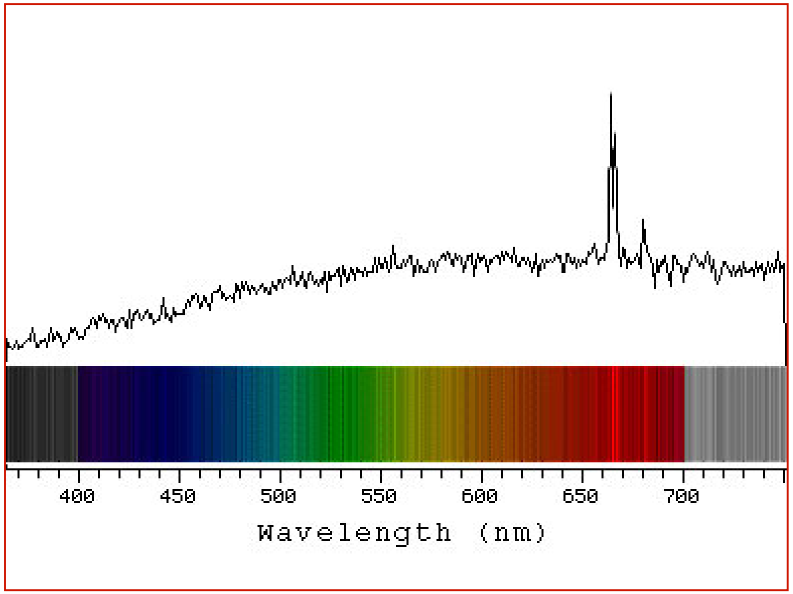


Expanding Universe



Galaxy UGC 12915

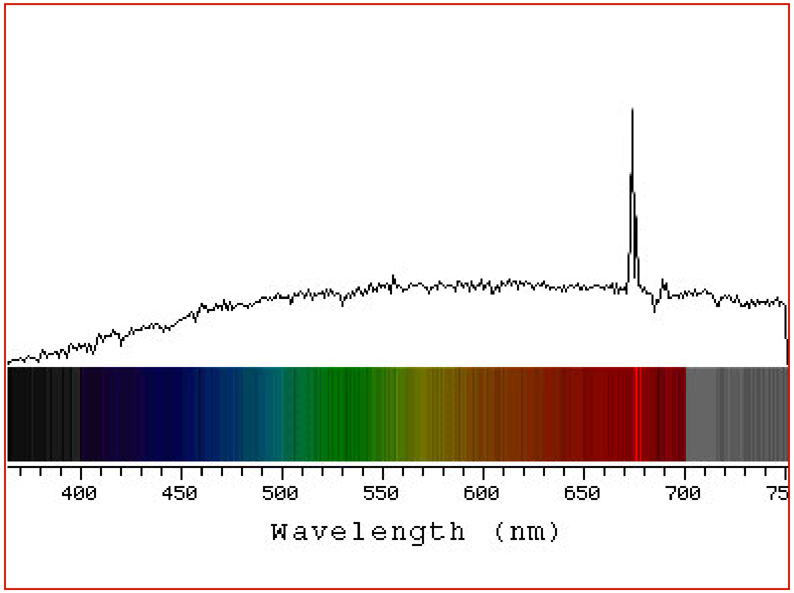
We see the same lines in the galaxy, but they are shifted to larger wave length (redshift)

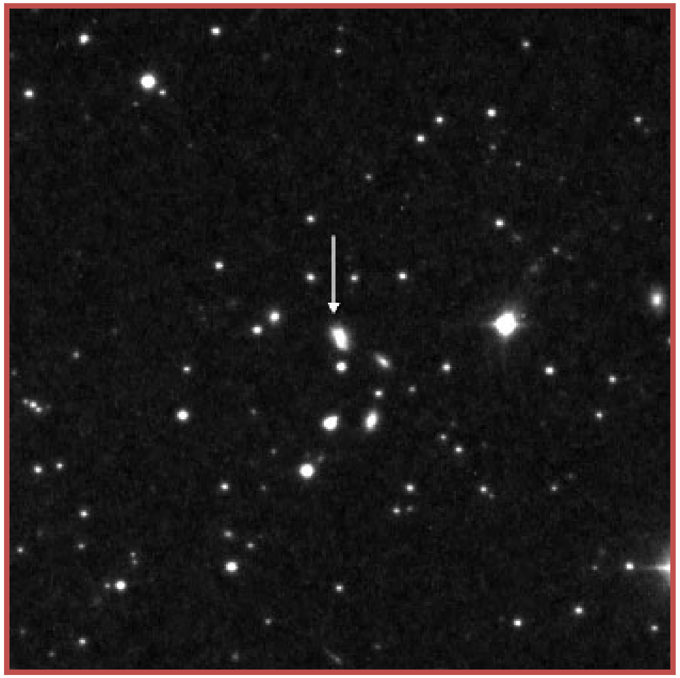


Expanding Universe

Galaxy UGC 12508

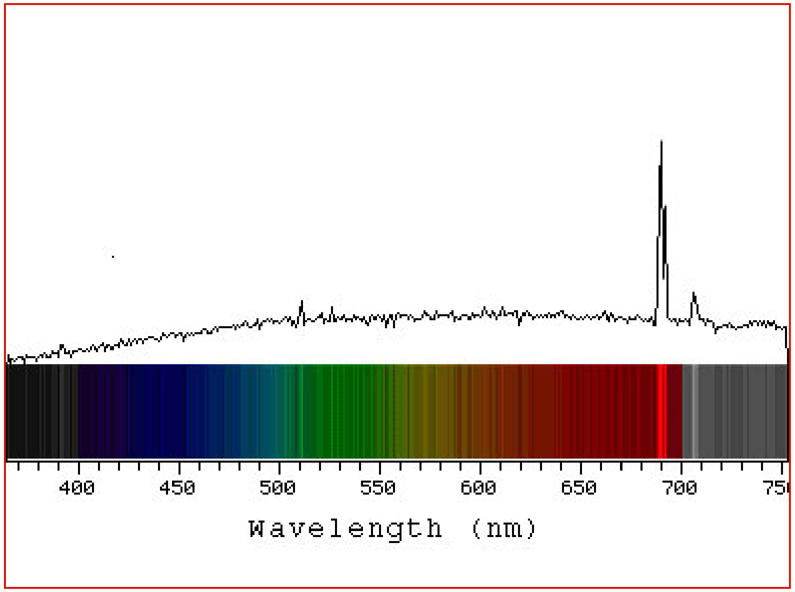
The further the galaxy is, the larger the redshift of the lines occur



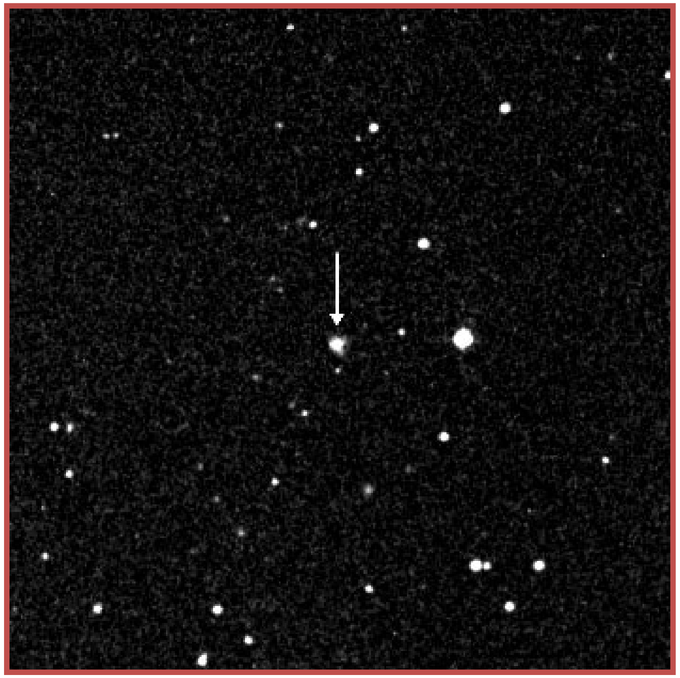


Galaxy KUG 1750

The larger the redshift, the further away is the galaxy

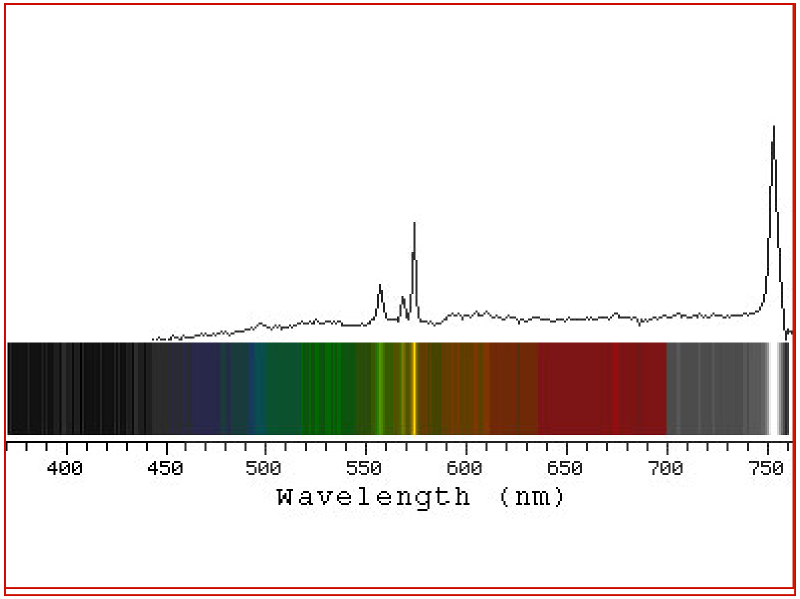


Expanding Universe



Galaxy KUG 1217

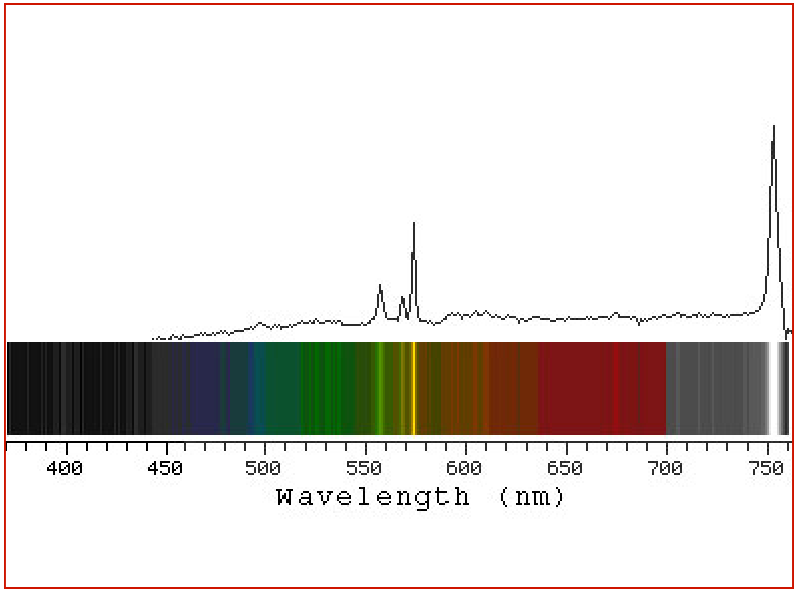
The redshift is caused by the expansion of space



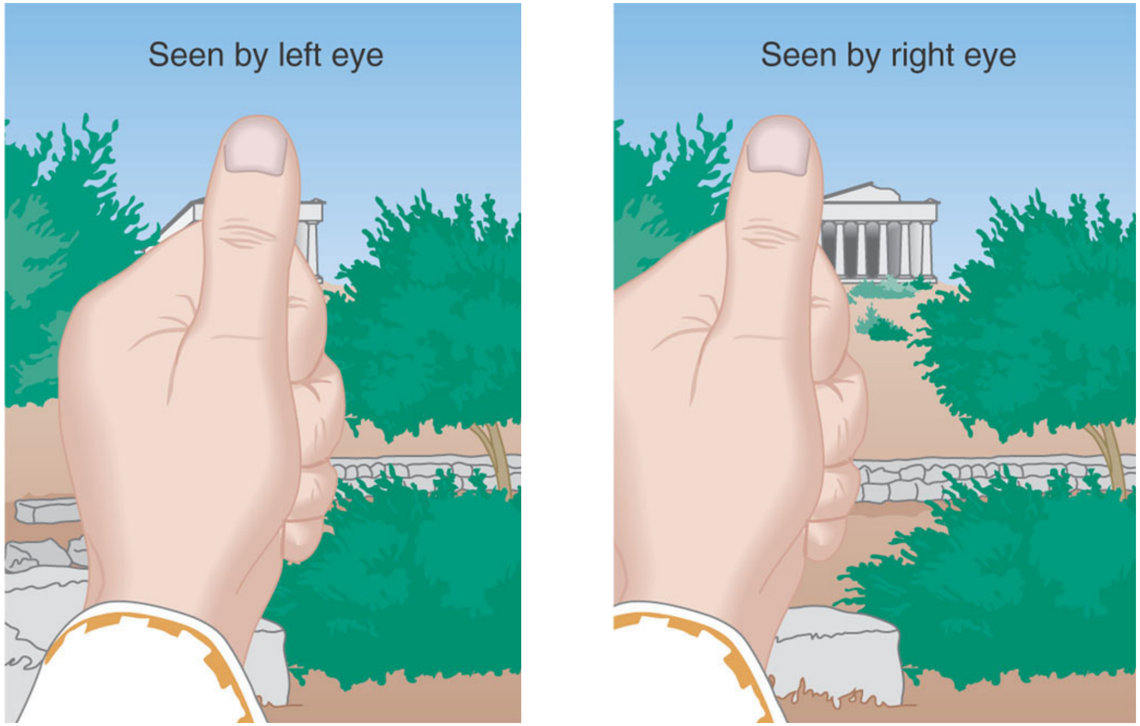
Expanding Universe

Galaxy IRAS F09159

The redshift is the proof for the expanding universe



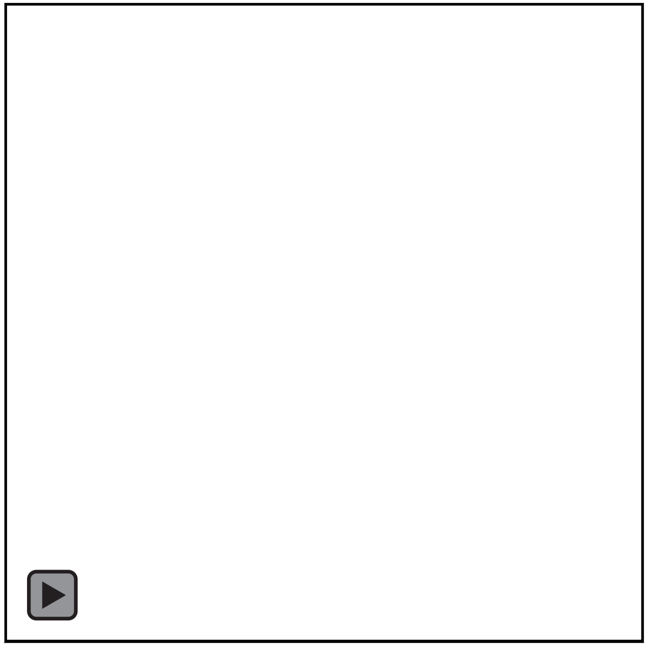
Determination of distances - paralax

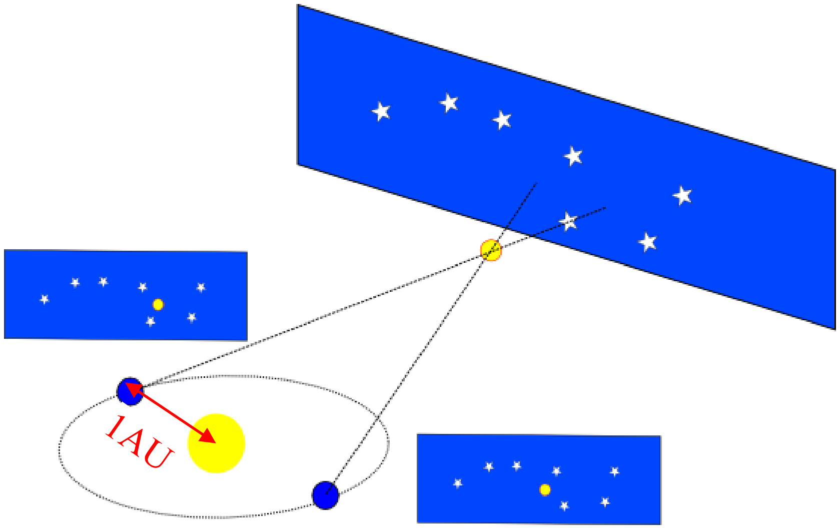


Trigonometry:

$$1'' \;\hat{=}\; 3{,}26\,Ly = 1\,pc$$

- Limited to stars no more than 100pc distance





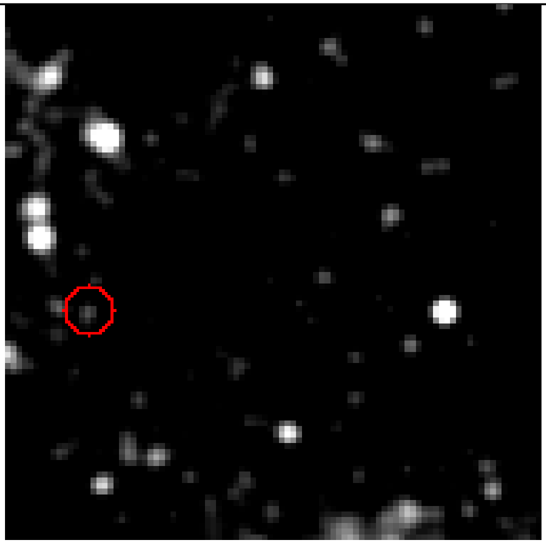
$$1\,arc\sec = \frac{1^0}{3600} = \frac{1^0}{3600}\cdot\frac{\pi}{180^0} = 4.85\cdot 10^{-6}\,rad$$

$$1\,Ly = 2.998\cdot 10^8\left(\frac{m}{s}\right)\cdot 86400\left(\frac{s}{d}\right)\cdot 365\left(\frac{d}{y}\right) = 9.46\cdot 10^{15}\,m$$

$$1\,pc = \frac{1.5\cdot 10^{11}\,m}{4.85\cdot 10^{-6}} = 3.086\cdot 10^{16}\,m = 3.26\,Ly$$

1parsec (pc) = unit of length, measures the distance of a star with a parallax of 1arc-second

Cepheid – intrinsic stellar pulsation

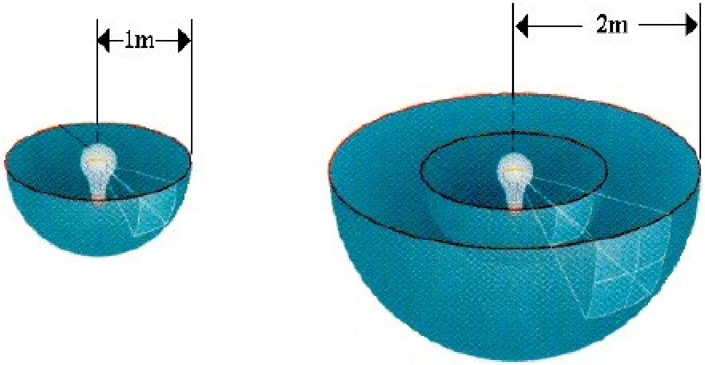


- Cepheids are stars, that undergo pulsations.
- (imbalance between ionization and gravitation)

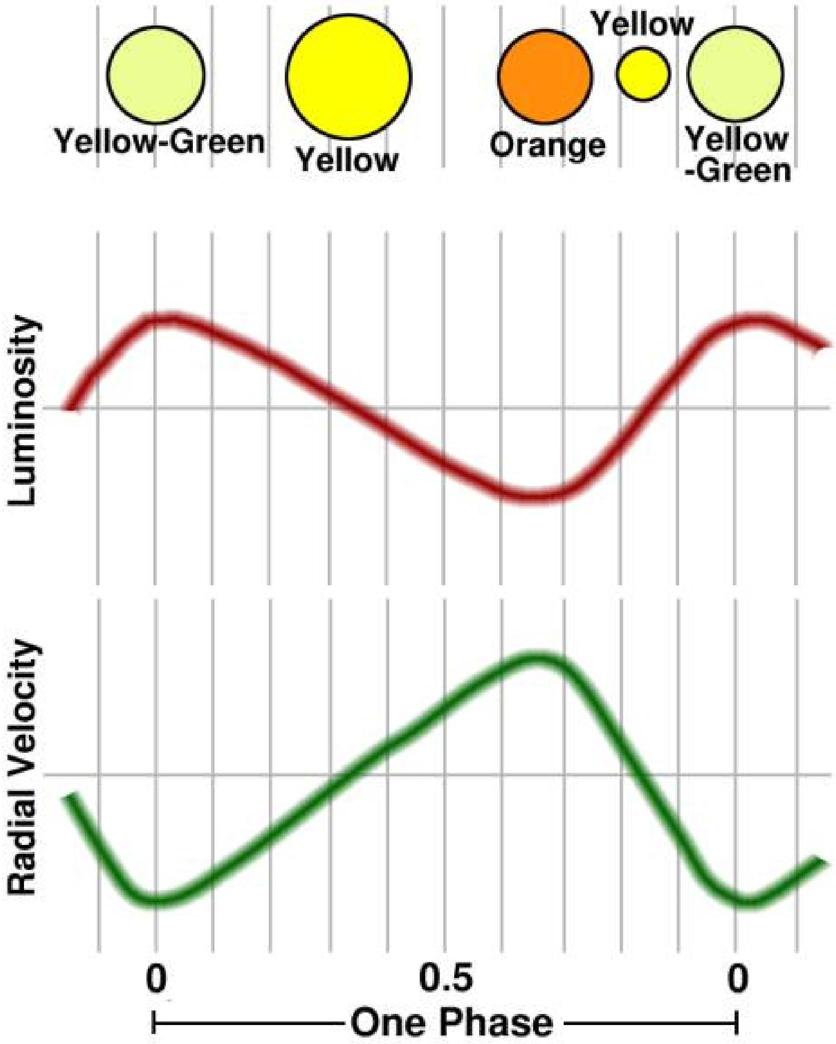
- 1912: H. Leavitt, H.Shapley:
- ➢ There is a linear relationship between luminosity and pulsation period.
- ➢ This method allows distance measurements up to 50 Mpc.

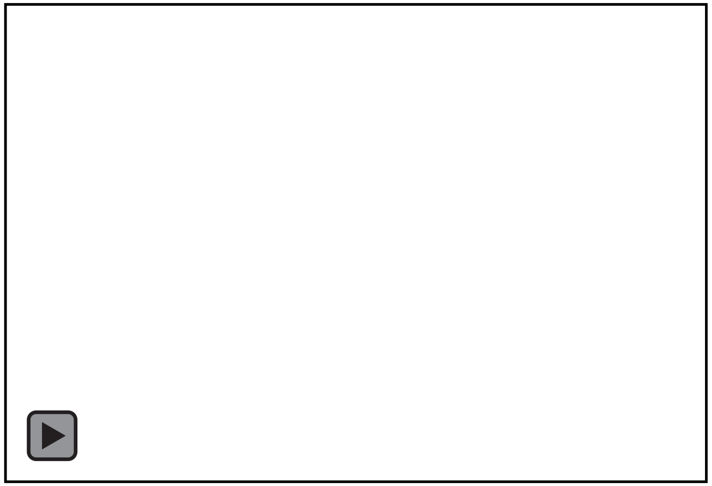
- If one measures the pulsation period of a Cepheid,
- one knows its true luminosity.
- One compares this with the observed brightness
- on Earth and obtains the cosmic distance to the star.

$$L_d = \frac{L_0}{4 \cdot \pi \cdot d^2}$$



Cepheids – intrinsic stellar pulsation



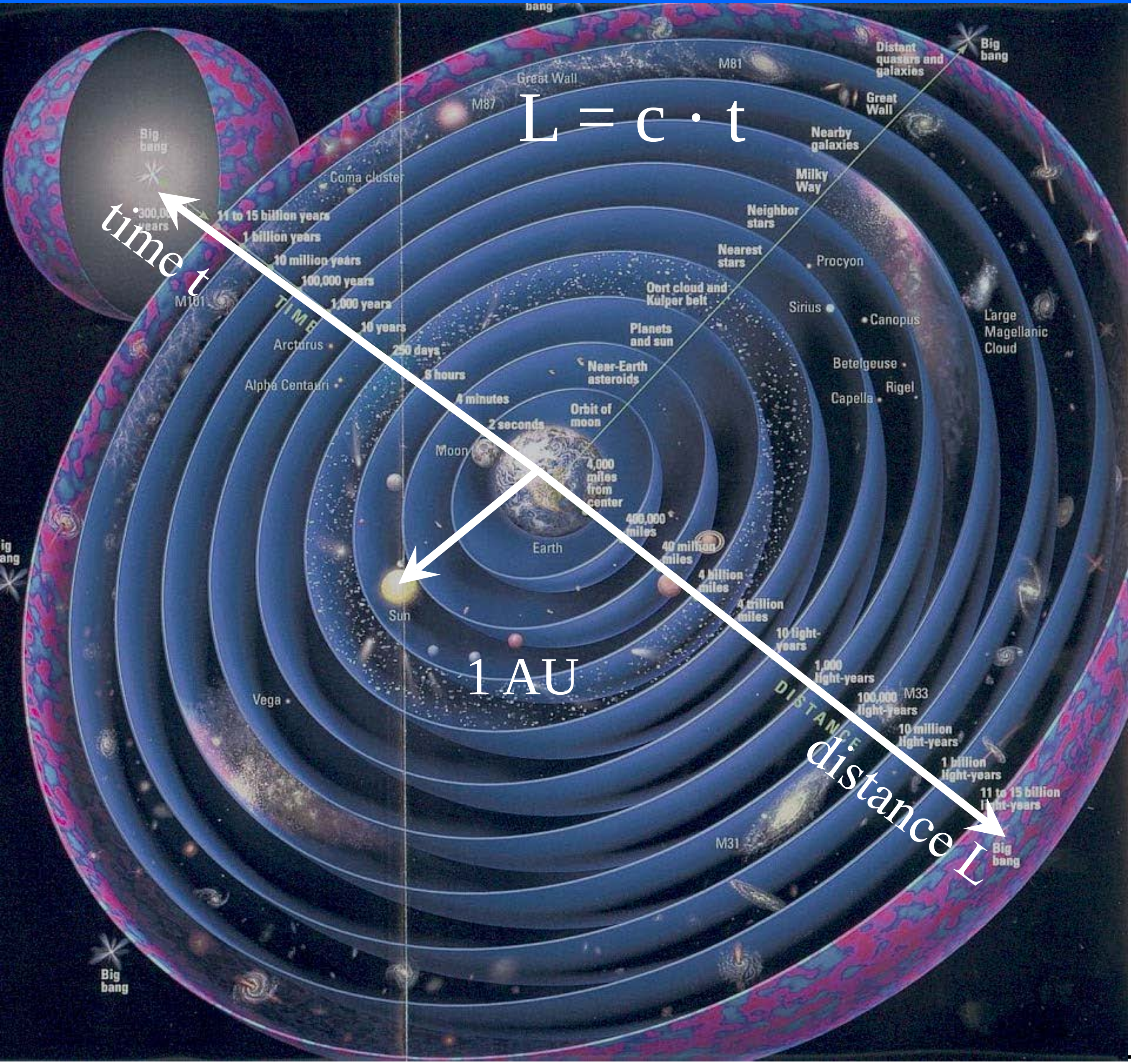


Luminosity:

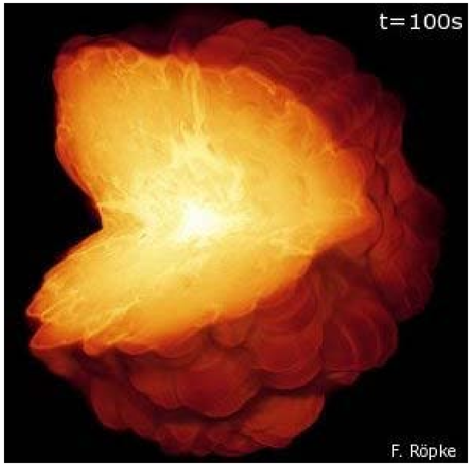
small but hot ***bright***

big but cool ***dim***

Cepheids – intrinsic stellar pulsation



50 Mpc – 3 Gpc



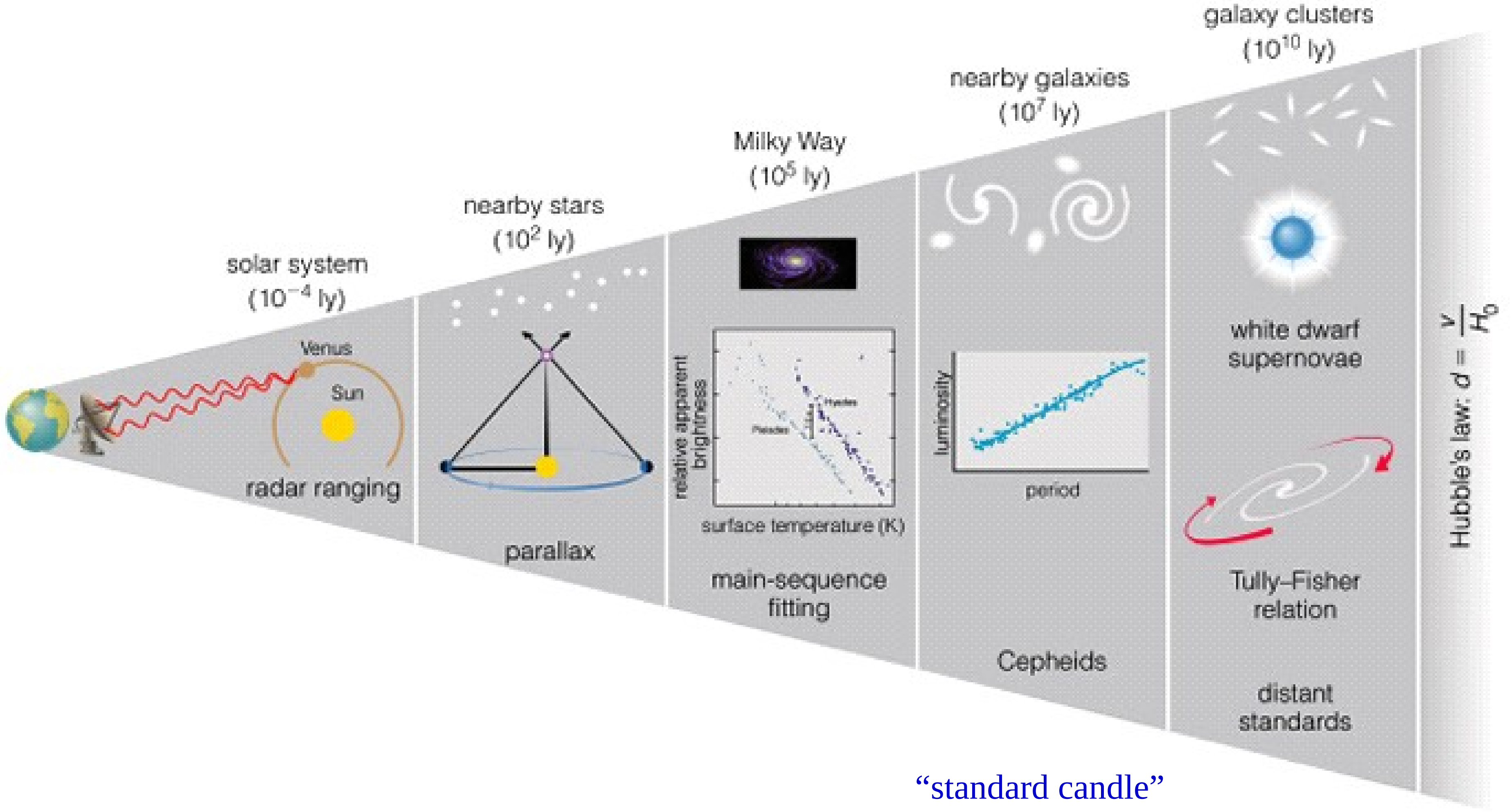
Supernovae Ia

1 astronomical unit (AU) =
$1.496 \cdot 10^{11}$ m

1 light year (ly) =
$9.461 \cdot 10^{15}$ m
= 63.240 AU = 0.3066 pc

1 Parsec (pc) =
$3.086 \cdot 10^{16}$ m
=2.06 ·105 AU = 3.262 ly

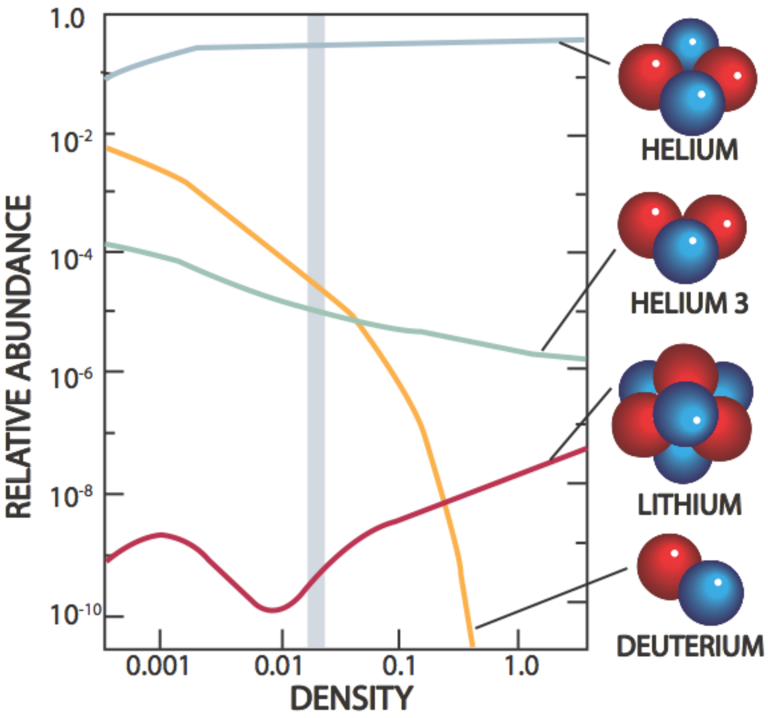
cosmic distance ladder



"standard candle"

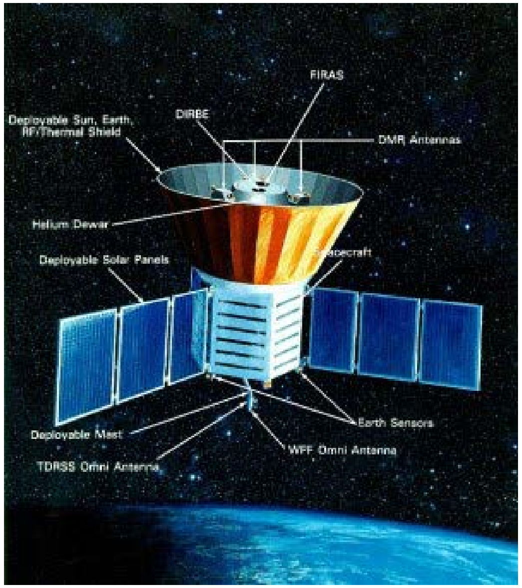
- Big Bang theory explains that protons and neutrons fused together to form deuterium and helium in the first few minutes of the Universe.

- The process where protons and neutrons combine to produce atomic nuclei is called nucleosynthesis.

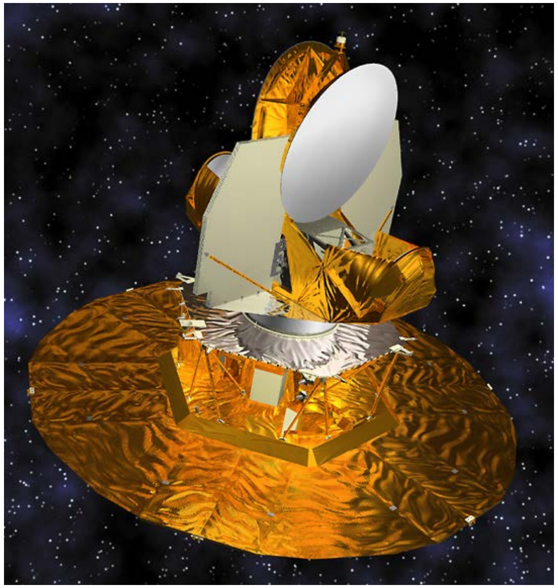


3. Cosmic microwave background radiation

Penzias, Wilson 1965



COBE satellite 1992



WMAP 2002

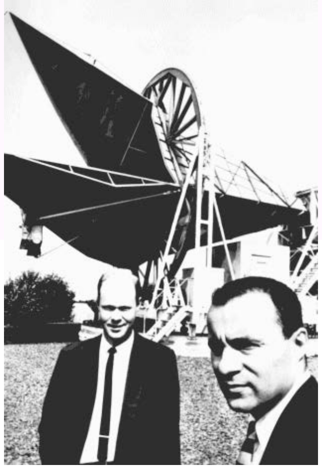
A. Penzias & R. Wilson 1965

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

May 13, 1965

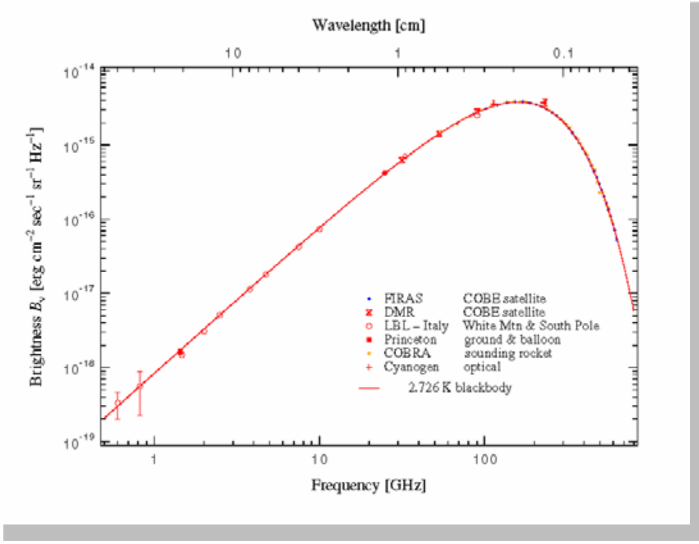
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

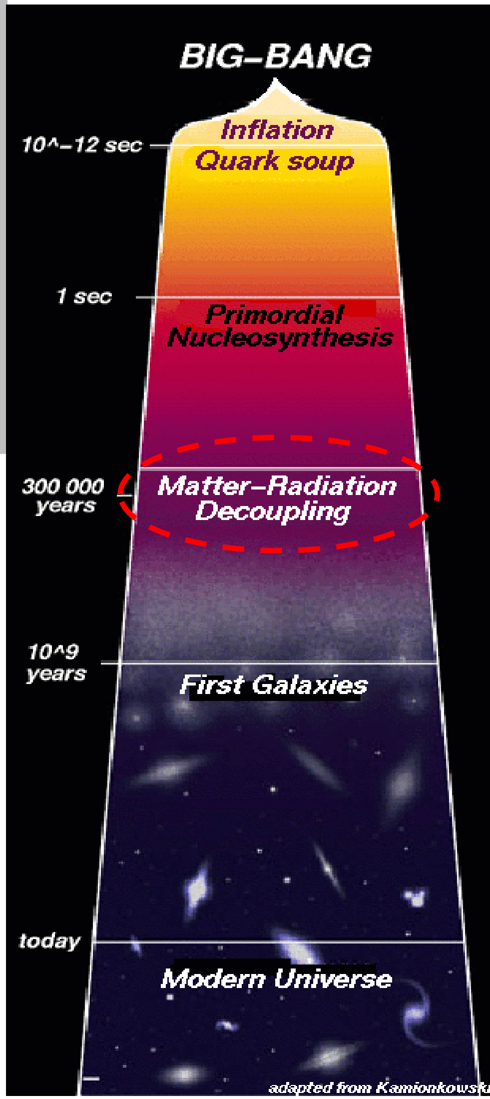


A. A. PENZIAS
R. W. WILSON

Interpretation of cosmic microwave background radiation

Cosmic microwave background radiation is exactly thermal
(black-body radiation)

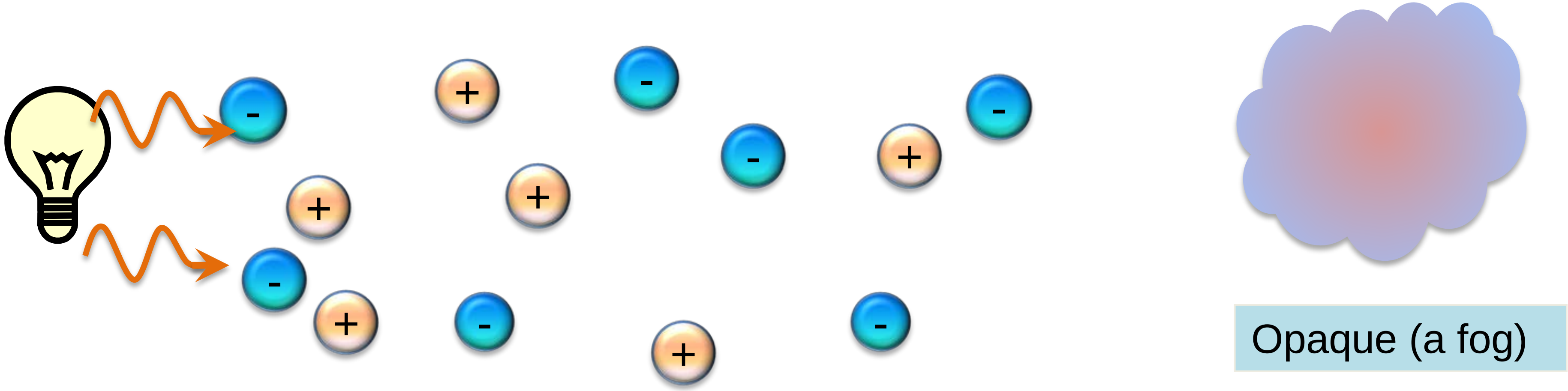




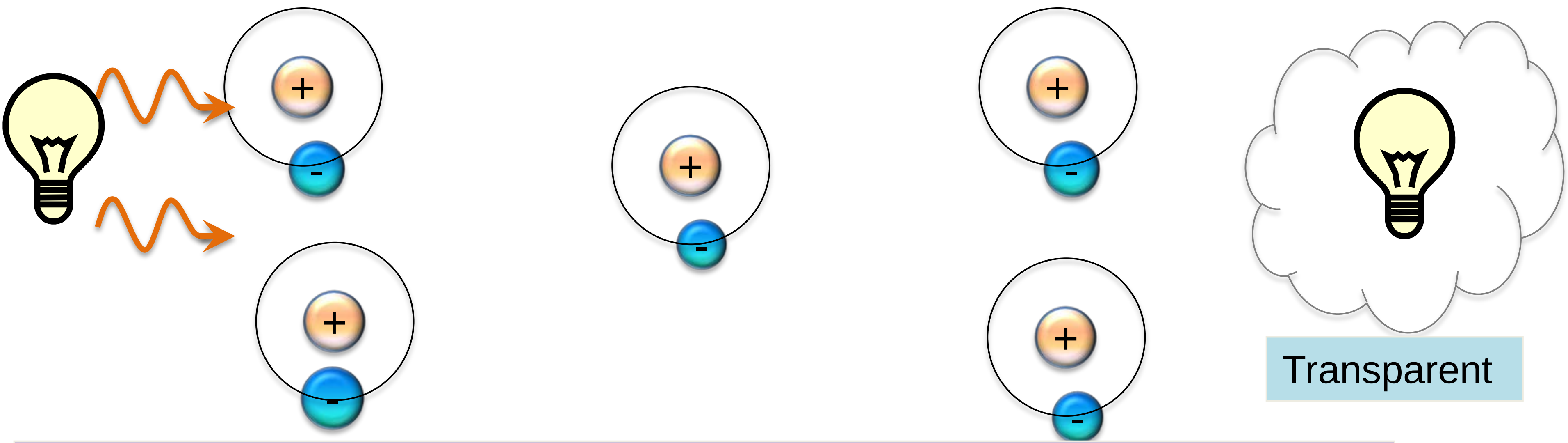
When the temperature dropped enough to allow electrons and protons to form hydrogen atoms – this occurred some 380 000 years after the Big Bang.
This event made the universe nearly transparent to radiation, because light was no longer being scattered of free electrons.

	380 000 y	today
size of universe	1	1100
frequency of light	1100	1
temperature	3000 K (0.26 eV)	2.725 K (0.2348 meV)

Photon-Matter interaction

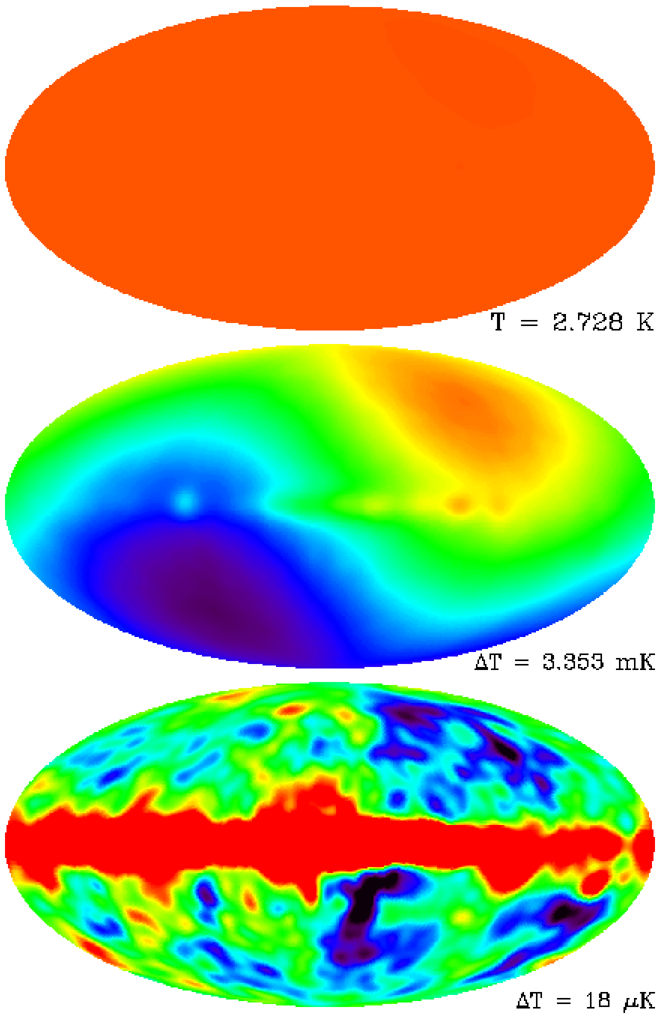


Photons of light interact strongly with free (ionized)electrons and protons



Photons of light rarely interact with stable atoms (paired electrons & protons)

COBE sky maps the most distant light



T = 2.7 K *isotropy* $T(z) = T_0 \cdot (1+z)$

scale

ΔT = 3.4 mK

(after subtraction of constant emission,

dipole anisotropy due to the motion of the Earth)

ΔT = 18 μK

(after subtraction of dipole, *fluctuations*,

the Milky Way has some emission in microwaves)

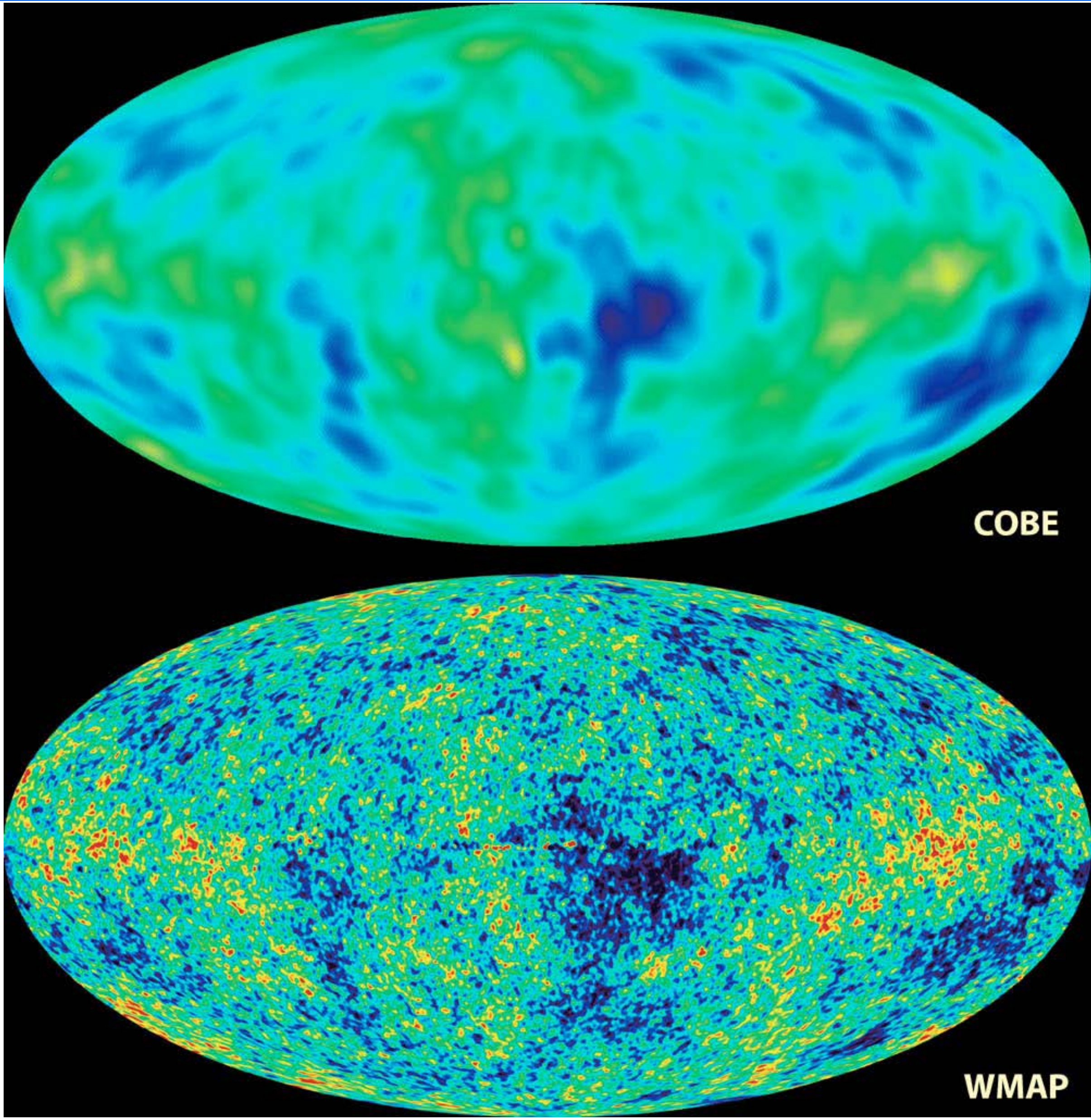
Measurement of cosmic microwave background radiation

very small temperature variations

red: T=2.725 K + 0,00002 K
blue: T=2.725 K – 0.00002 K

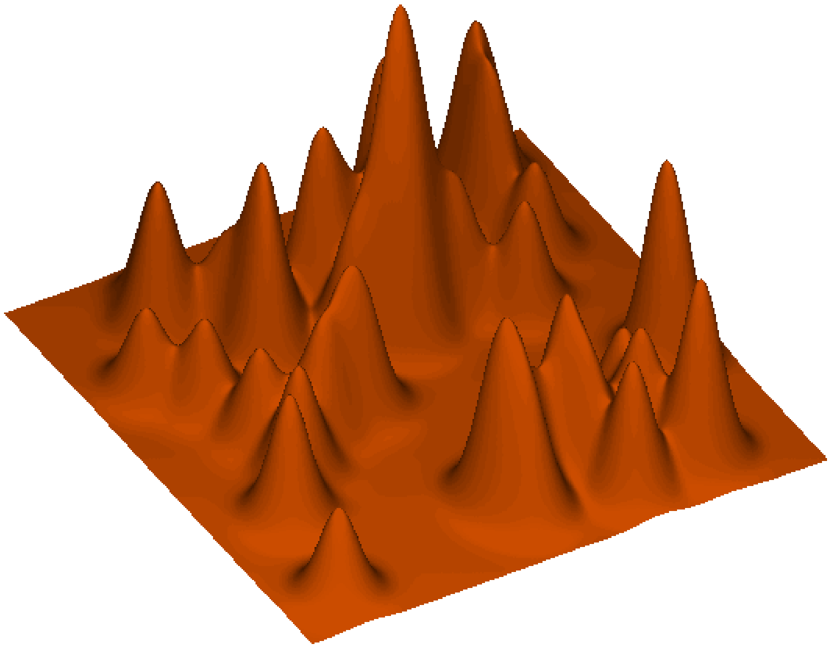
Isotropic?

CMB is anisotropic!
(at the 1/100,000 level)



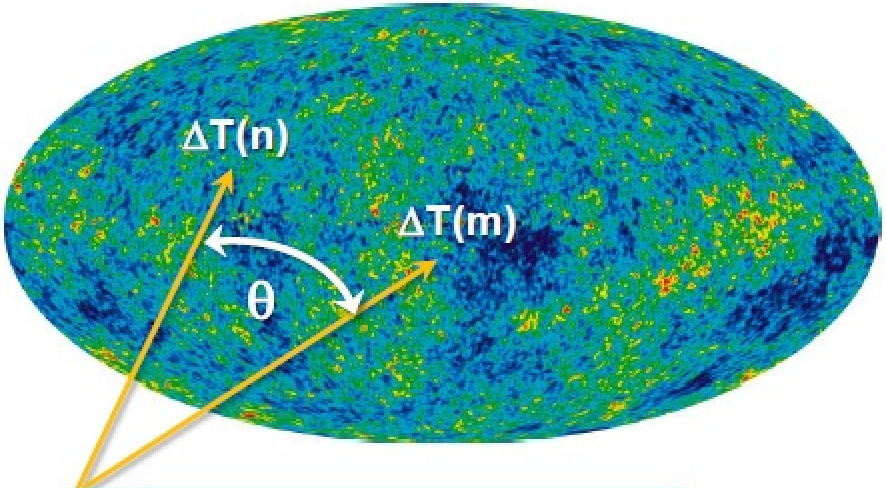
Where do the spots come from?

- Quantum mechanical energy fluctuations during inflationary period.
- These fluctuations pulse through the universe as sound waves.
- When the universe become transparent sound waves are frozen in (light and matter are decoupled)



Multipole expansion

- statistical analysis of the temperature fluctuations ΔT with respect to the average temperature T_0 using the correlation function C(θ)



- expansion with respect to spherical harmonics using the coefficients $\alpha_{\ell m}$

$$T(\vec{n}) = T_0 \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{m=+\ell} a_{\ell m} Y_{\ell m}$$

for Gauss fluctuations:

$$C(\theta) = \left\langle \left(\frac{\Delta T(\vec{n})}{T_0} \right) \left(\frac{\Delta T(\vec{m})}{T_0} \right) \right\rangle$$

coefficient C_ℓ

$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

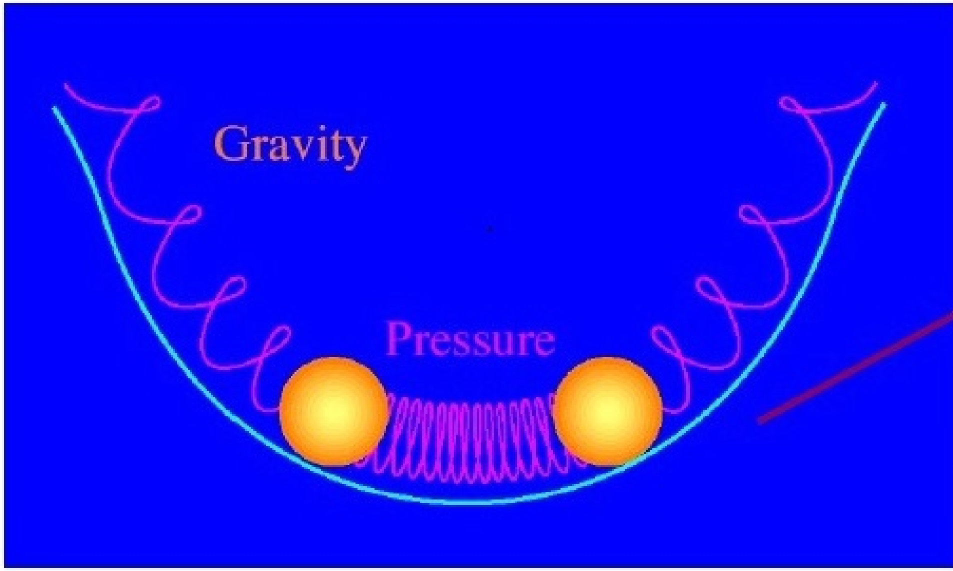
expansion of Legendre polynomes

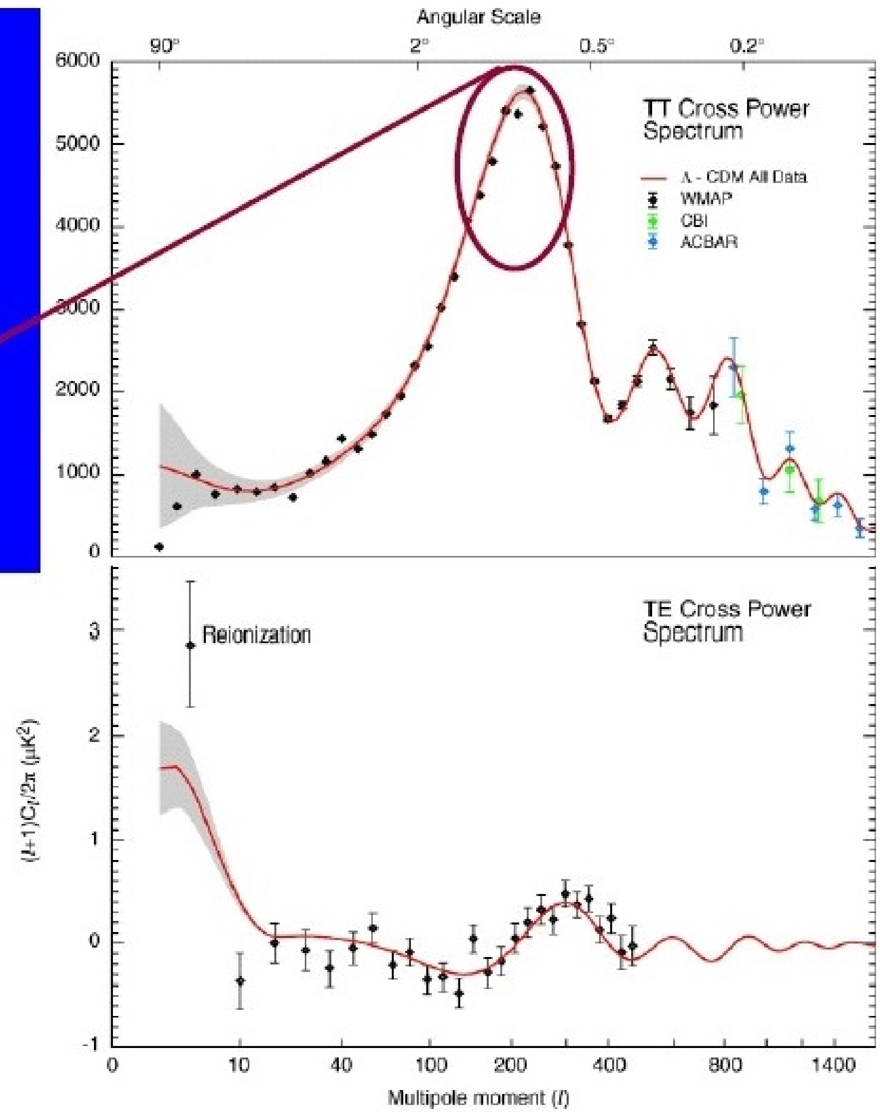
$$C(\theta) = \frac{1}{4\pi} \sum_{\ell} (2\ell+1) C_\ell P_\ell(\cos\theta)$$

cosmic variance

correlation function C(θ)

Acoustic oscillation Cosmic microwave background radiation





radiation pressure causes expansion

gravitation causes compression

matter as plasma in equilibrium

Basic idea: Hit it and listen to the cosmic sound

multipole expansion

What is still uncertain?

1. Why did inflation occur?

2. Standard model doesn't predict fundamental constants (masses, charges, speed of light, etc.
   - Anthropic principle: If constants were even a little different, we wouldn't be here to puzzle about them!

3. Why is energy density of the vacuum so close to the energy density of matter.
   - Particle physics predicts ratio should be $\sim 10^{120}$!

4. Is there only one Universe or are there 'many Universe bubbles?'
   - Inflation allow for such disconnected space-time 'bubbles'

5. What was before the Big Bang?
   - String theory avoids singularity at t=0 (in 10-dimensional space-time)