

# Reading

1. Today, we are covering material of [S 26-6, 26-7 \(Ch. 26\)](#) on the use of SNIa as standard candles and discovery of the apparent acceleration of the Universe in the last few billion years.
2. [S 20-9](#) in Ch. 20 discusses the SN type Ia progenitors and their properties.

The idea of inflationary rapid expansion during the earliest stages

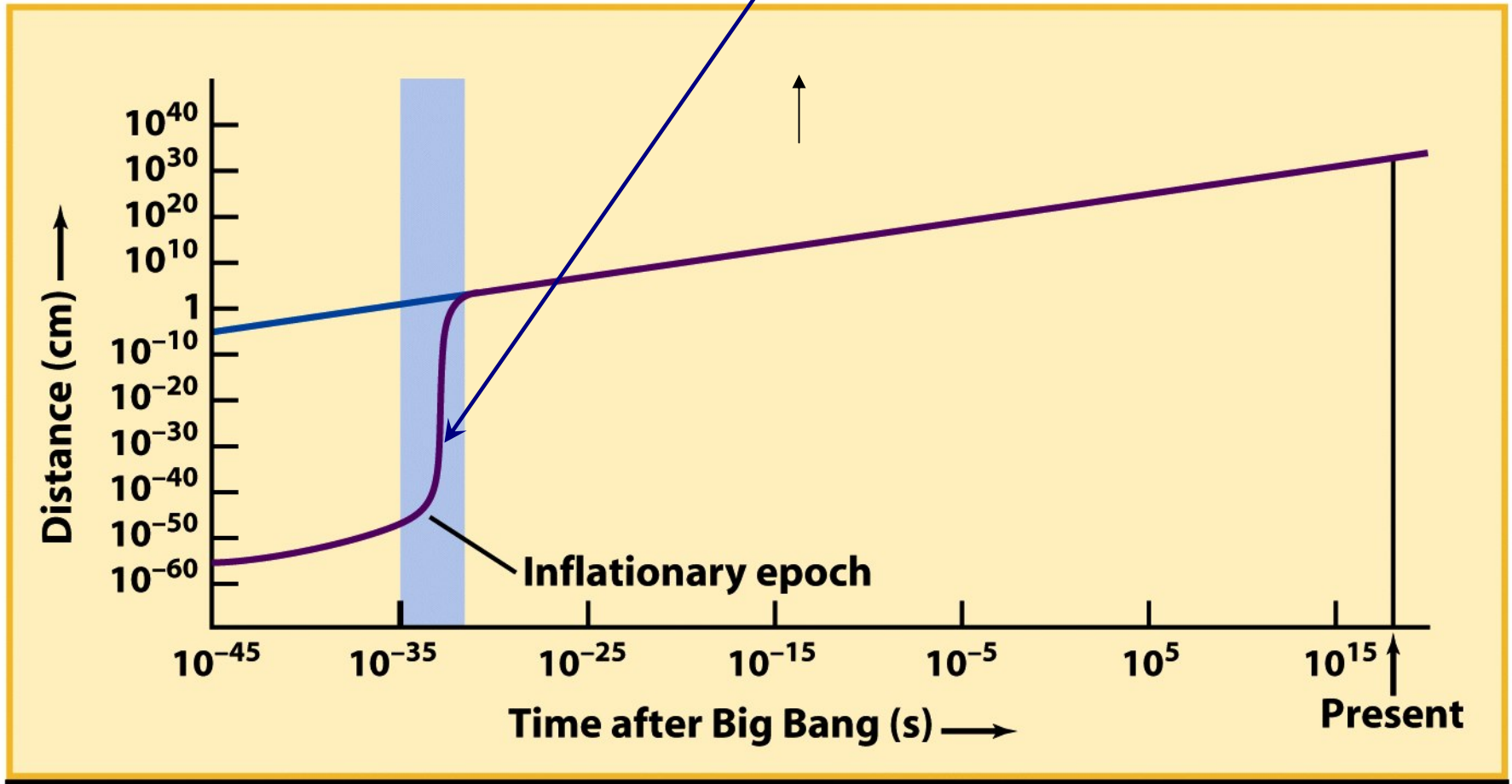
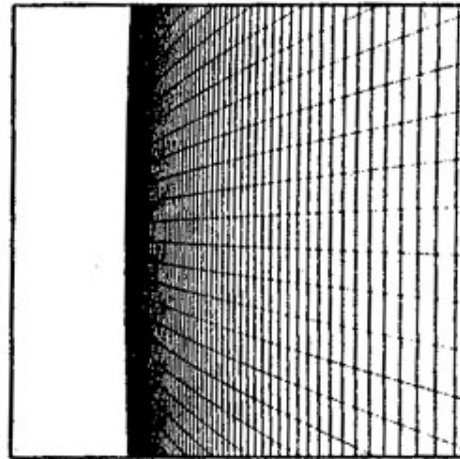
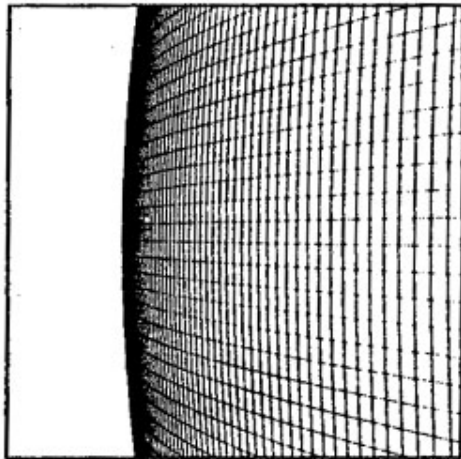
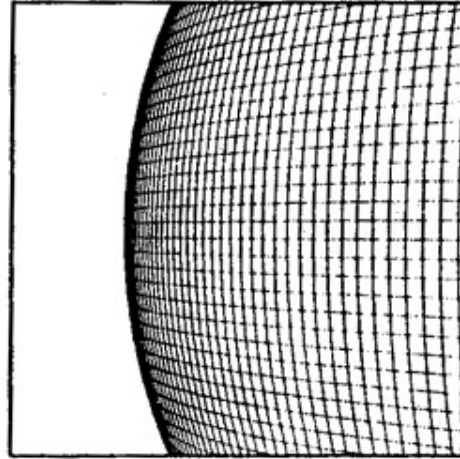
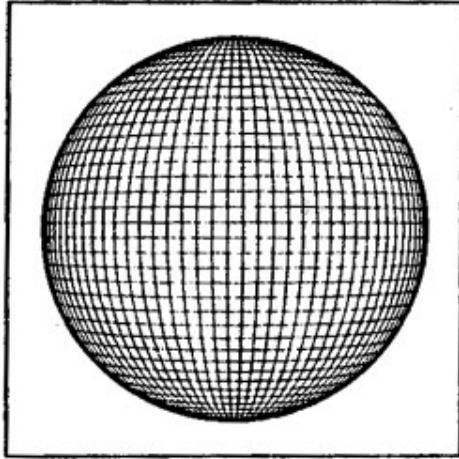
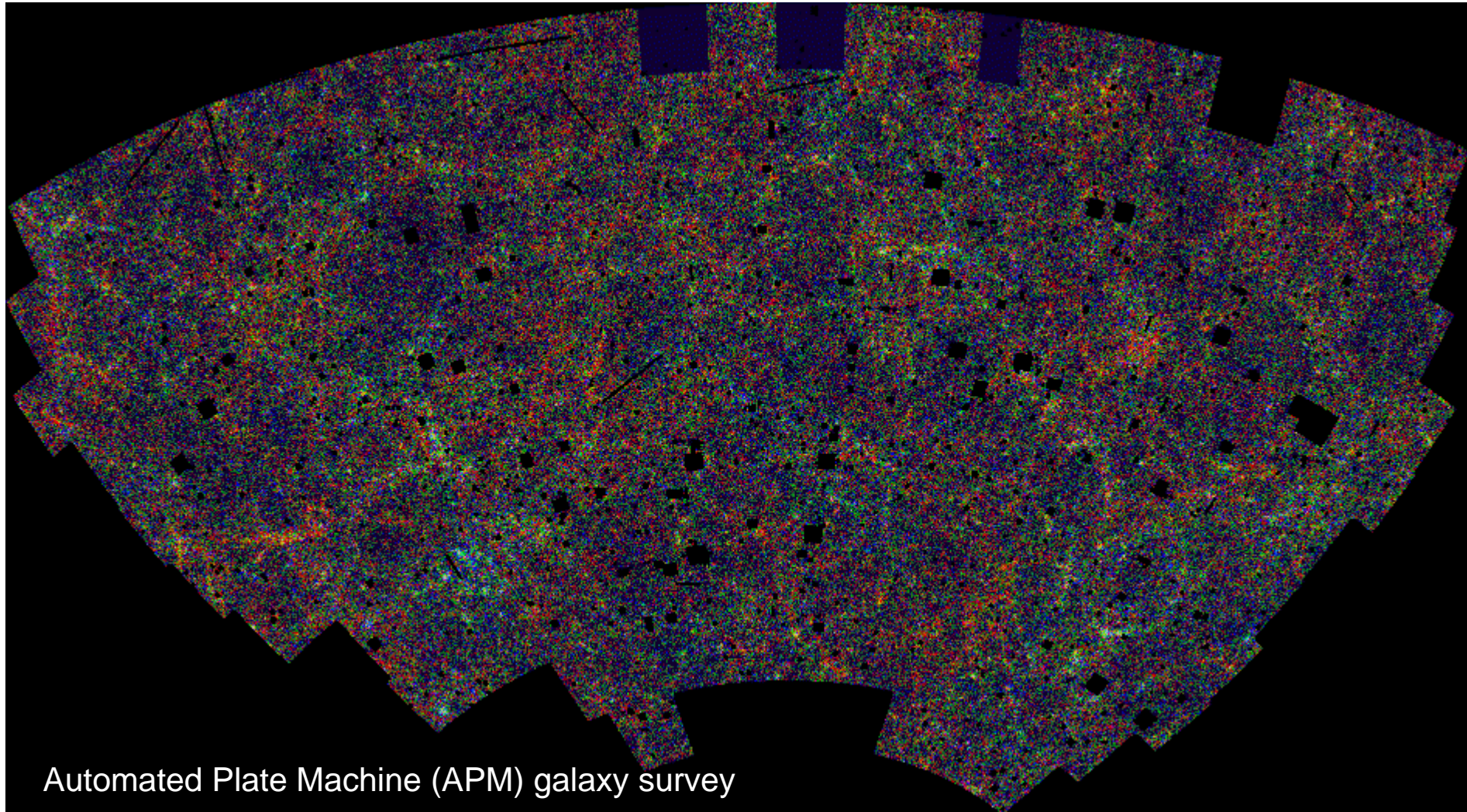


Figure 27-2  
*Universe, Eighth Edition*  
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Rapid expansion "stretches" space  
making it locally flat



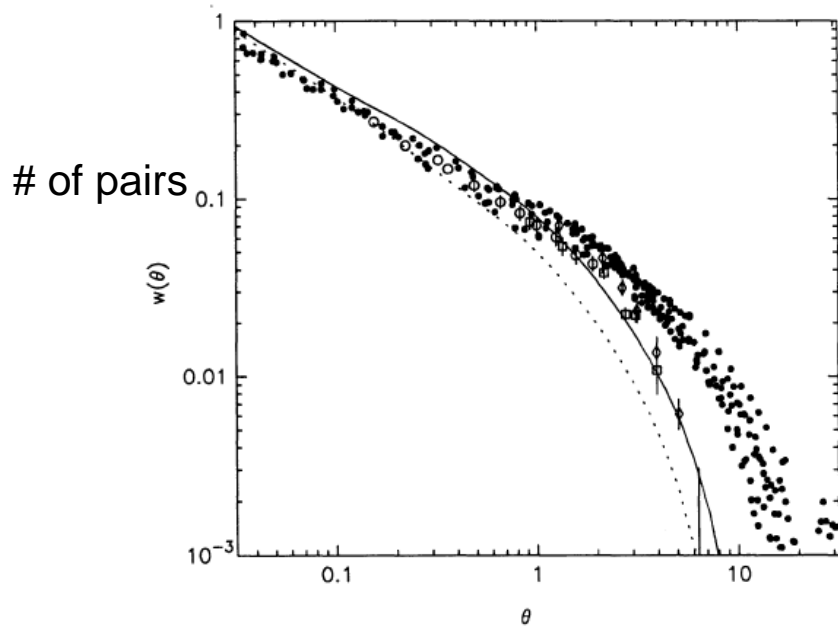
First indirect evidence for accelerating universe appeared in the early 90s



Automated Plate Machine (APM) galaxy survey

# First indirect evidence for cosmological constant appeared in the early 90s

*George Efstathiou and colleagues showed that galaxies in the APM surveys were clustered more strongly than expected in an  $\Omega_m=1$  Universe that this could be explained by the presence of cosmological constant*



angular separation on the sky  
between galaxies in a pair



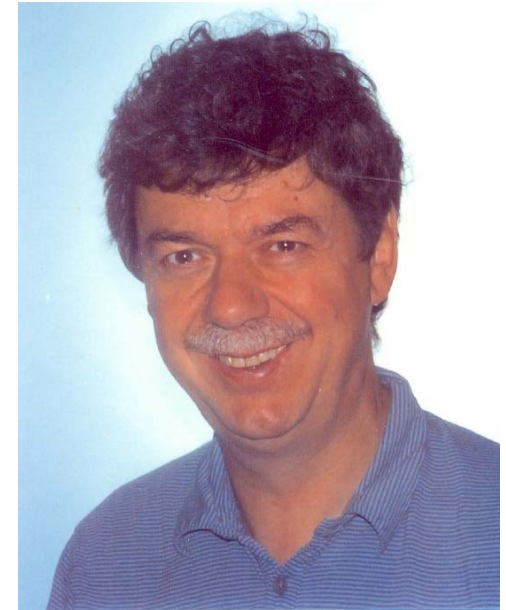
George Efstathiou (Cambridge)

# Baryon content of clusters

Observations in the early 1990s showed that the mass fraction of baryons in clusters is about 3 times larger than expected in an  $\Omega_m=1$  Universe



*a cluster of galaxies*



Simon White  
(Max Planck Institute, Germany)  
and collaborators have presented  
argument in 1993 that mass  
fraction of baryons in  
galaxy clusters  
indicates that density of matter  
is considerably less than critical.

# General Relativity Theory of Gravity



Albert Einstein  
writing down the Riemann tensor  
which describes local  
curvature of space

equation of Einstein's general relativity theory of gravity can be written simply as:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

*GEOMETRY = MATTER + ENERGY*

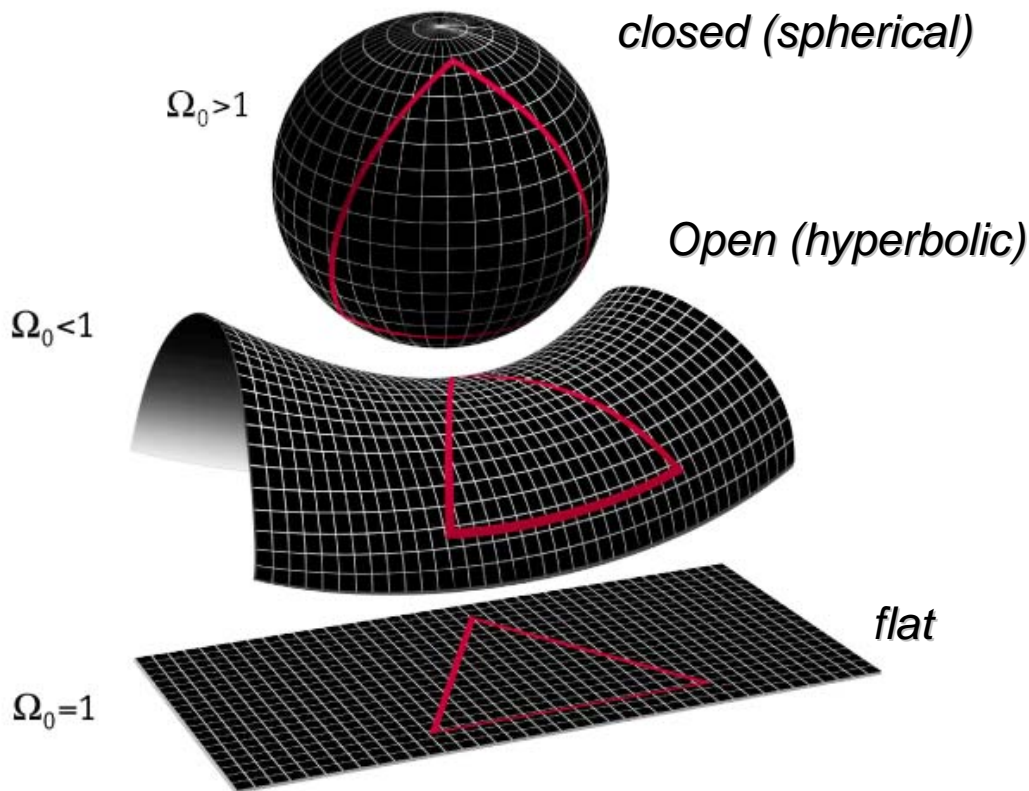
applied to the Universe as a whole together with the cosmological principle (assumption the the Universe is homogeneous and isotropic) gives expansion rate as a function of time

# Friedmann equation

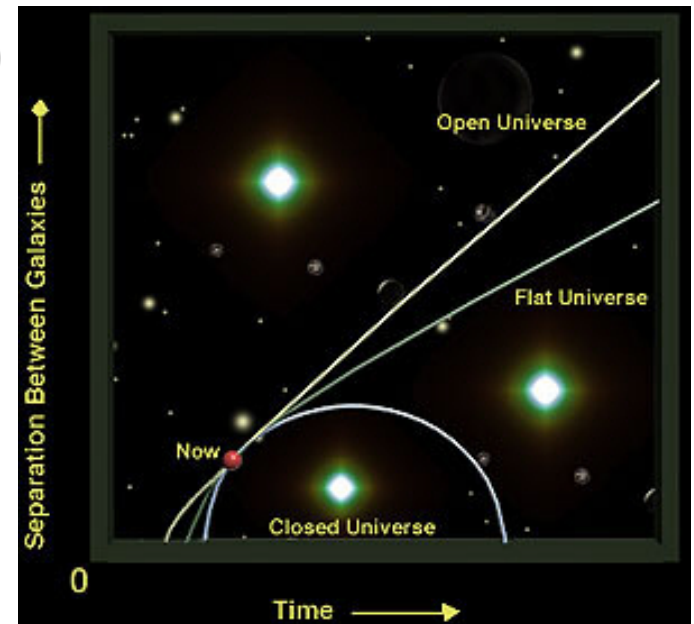
shows that matter/energy content and curvature of space in the universe are linked

$$\Omega_m = \rho_m / \rho_c, \quad \Omega_\Lambda = \rho_\Lambda / \rho_c, \quad \Omega = \Omega_m + \Omega_\Lambda \quad \rho_c = \frac{3H^2}{8\pi G}$$

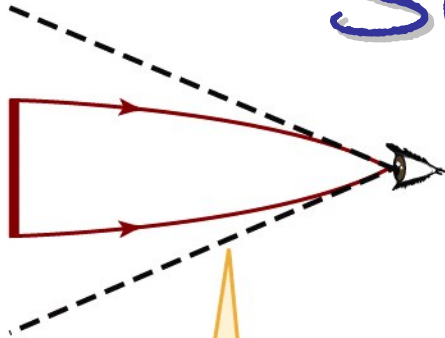
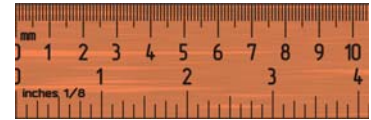
The *current* critical density is approximately  $10^{-29}$  g/cm<sup>3</sup>.



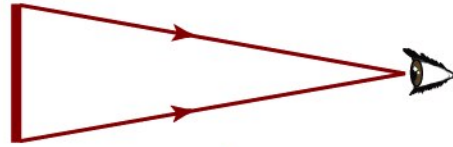
**In general, all matter and energy contribute to Omega**



# Standard rulers



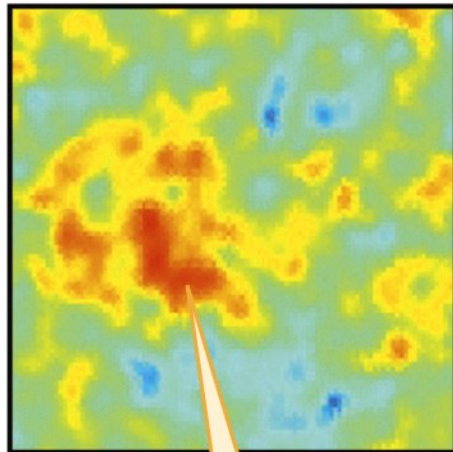
If the universe is closed, light rays from opposite sides of a hot spot bend toward each other ...



If the universe is flat, light rays from opposite sides of a hot spot do not bend at all ...

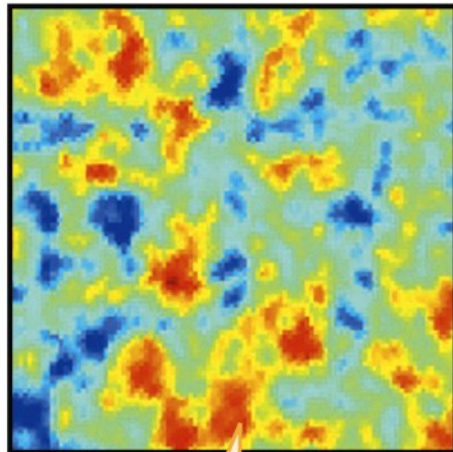


If the universe is open, light rays from opposite sides of a hot spot bend away from each other ...



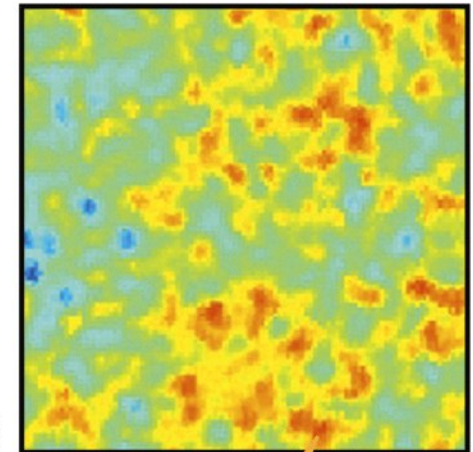
(a)

... and as a result, the hot spot appears to us to be larger than it actually is.



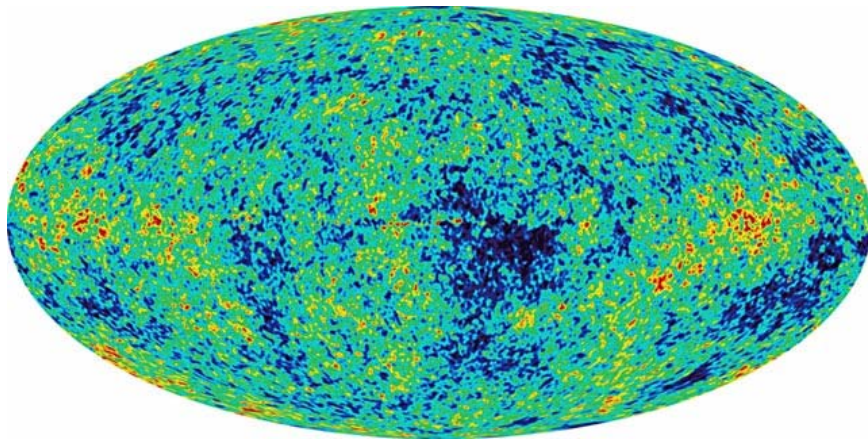
(b)

... and so the hot spot appears to us with its true size.

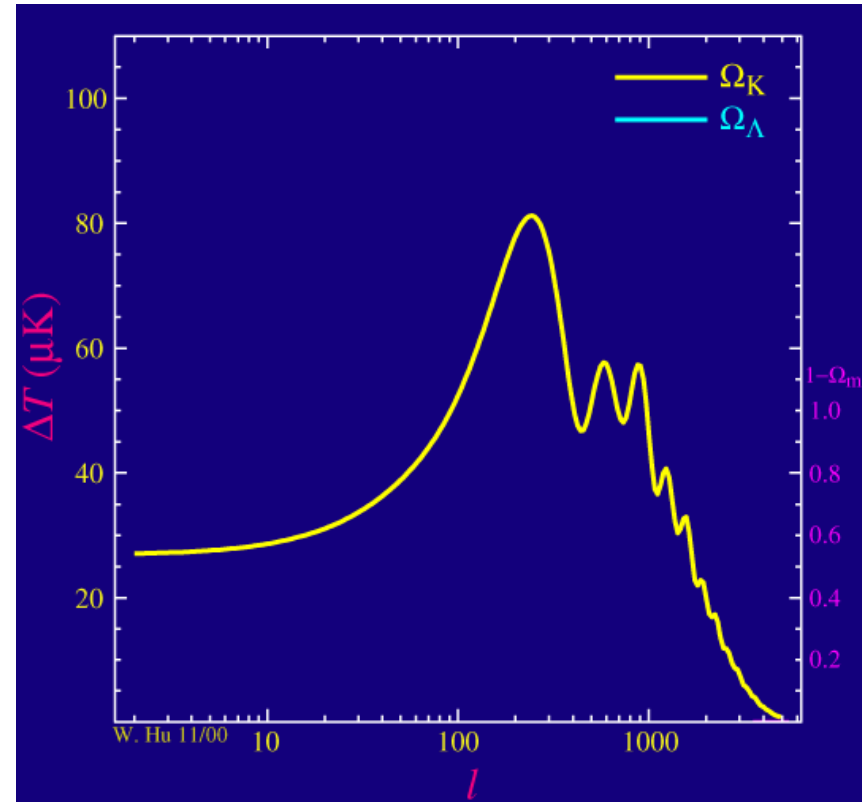
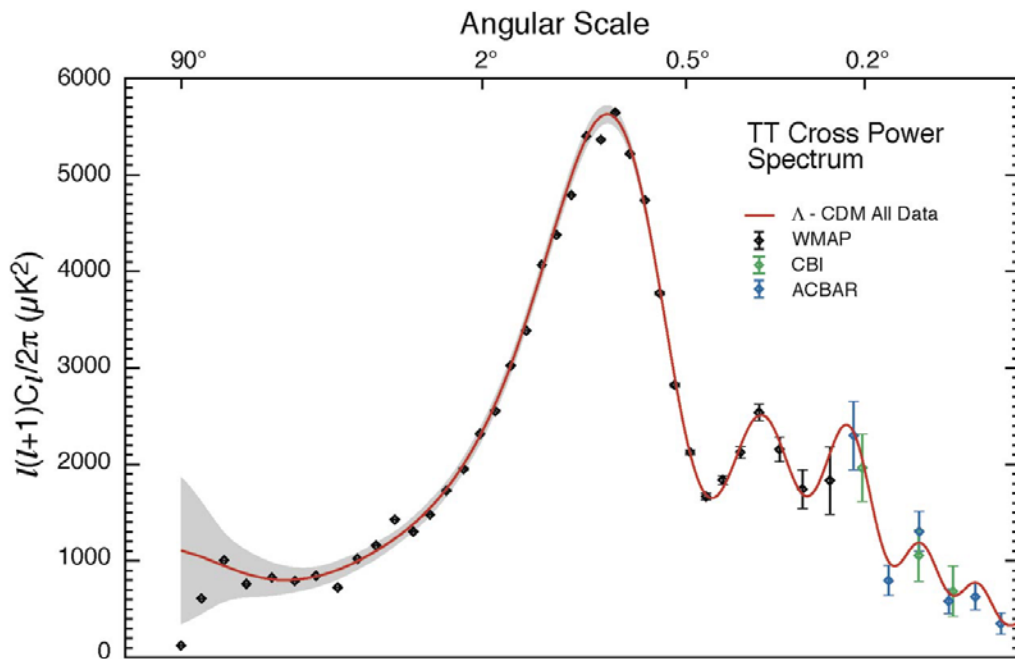


(c)

... and as a result, the hot spot appears to us to be smaller than it actually is.

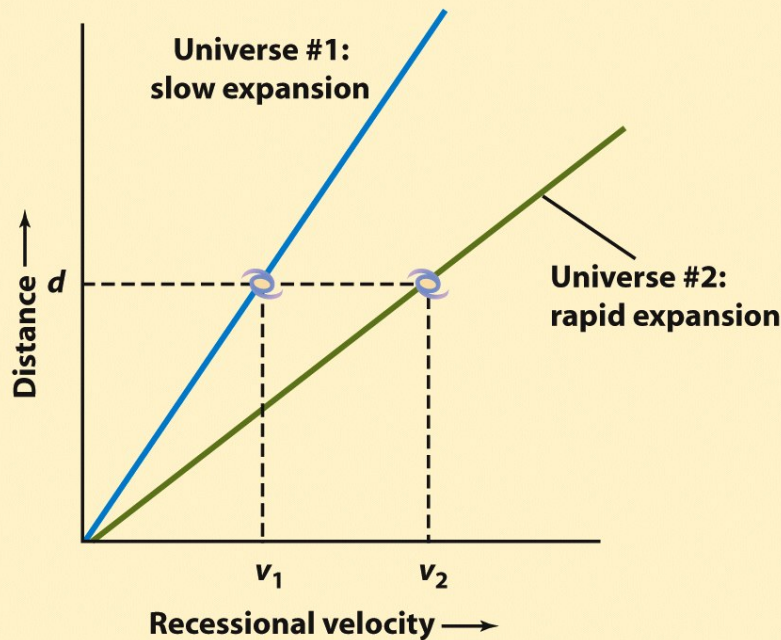


Modern measurements of the CMB temperature fluctuation spectrum



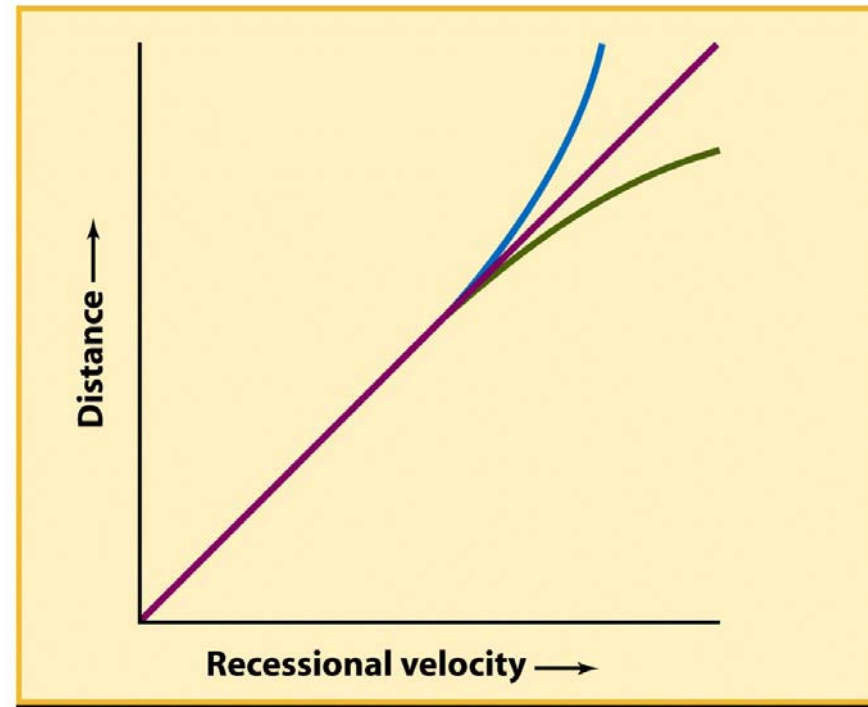
# Another way to constrain cosmological parameters: distance-redshift relation

Universe #2 expands at a faster constant rate than Universe #1, so a galaxy at a given distance  $d$  has a greater recessional velocity in Universe #2 than in Universe #1.



**Two universes with different expansion rates**

Figure 26-17a  
*Universe, Eighth Edition*  
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**Possible expansion histories of the universe**

Figure 26-17b  
*Universe, Eighth Edition*  
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# Standard candles



Most methods of measuring distances in the cosmic “distance ladder” rely on some way of estimating the intrinsic brightness (luminosity) of object.

Comparing intrinsic and apparent brightness the distance can be estimated:

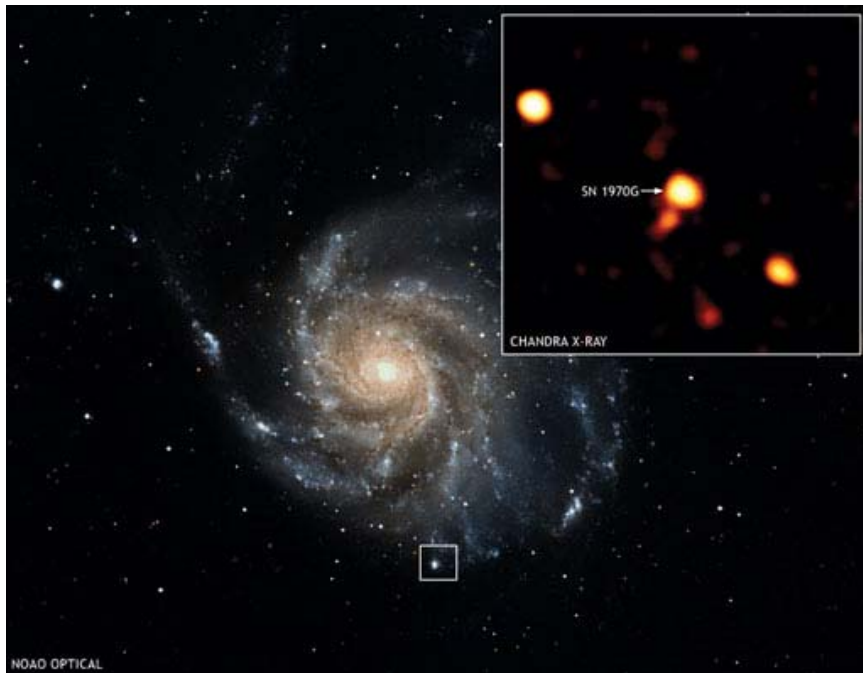
$$B = \frac{L}{4\pi d^2} \Rightarrow d_L = \sqrt{\frac{L}{4\pi B}}$$

The diagram shows the equation  $B = \frac{L}{4\pi d^2} \Rightarrow d_L = \sqrt{\frac{L}{4\pi B}}$  with arrows pointing from labels to variables: "apparent brightness" points to  $B$ , "luminosity" points to  $L$ , and "distance" points to  $d_L$ .

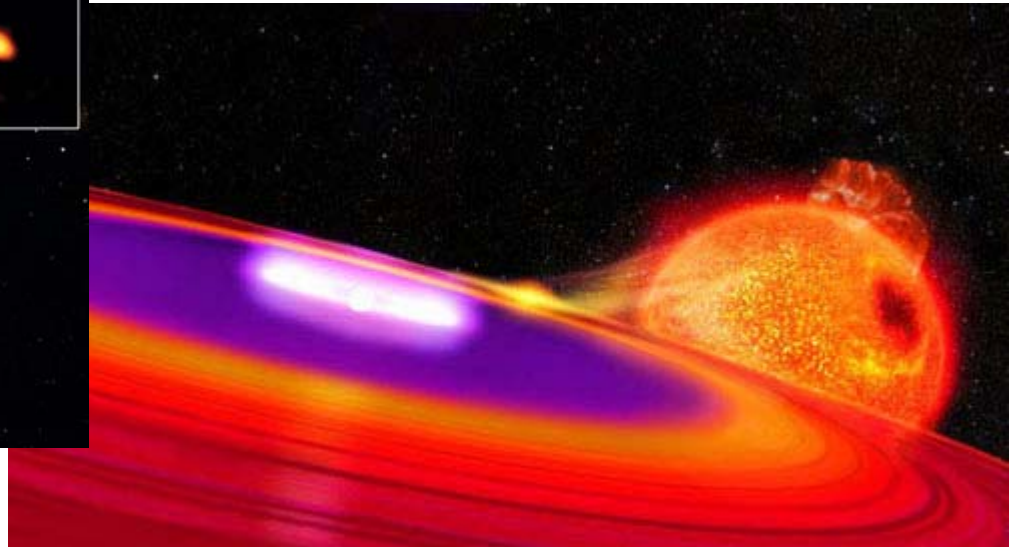


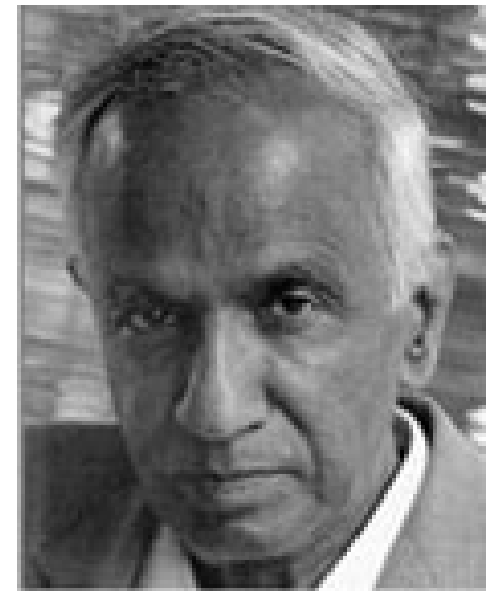
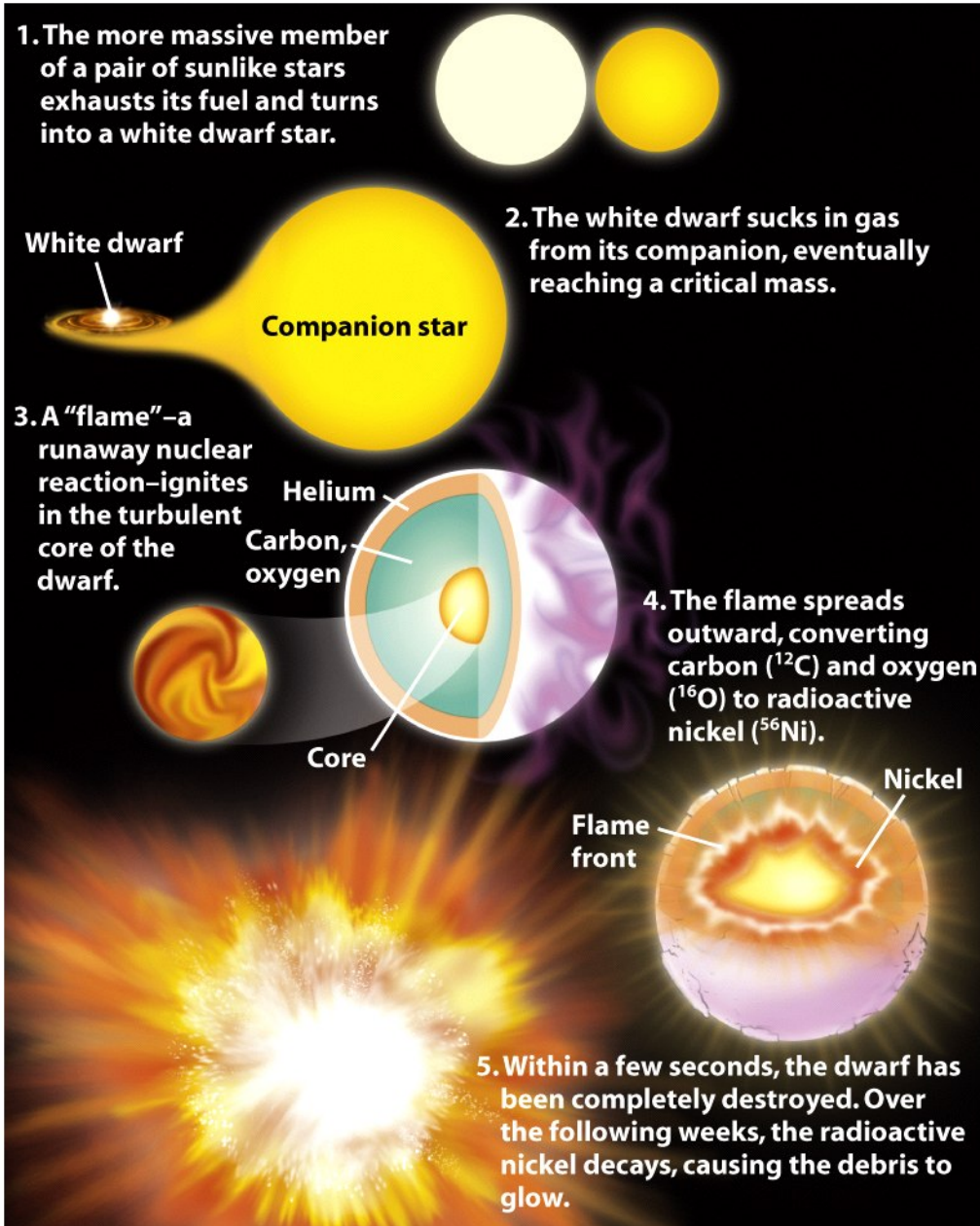
# Supernovae type Ia (SNIa) as “standard candles”

**Supernovae are exploding stars which for some period of time reach brightness comparable to the brightness of their host galaxy (billions of stars combined)**



**SNIa are special kind of supernova that are thought to originate in white dwarf stars in binary systems**





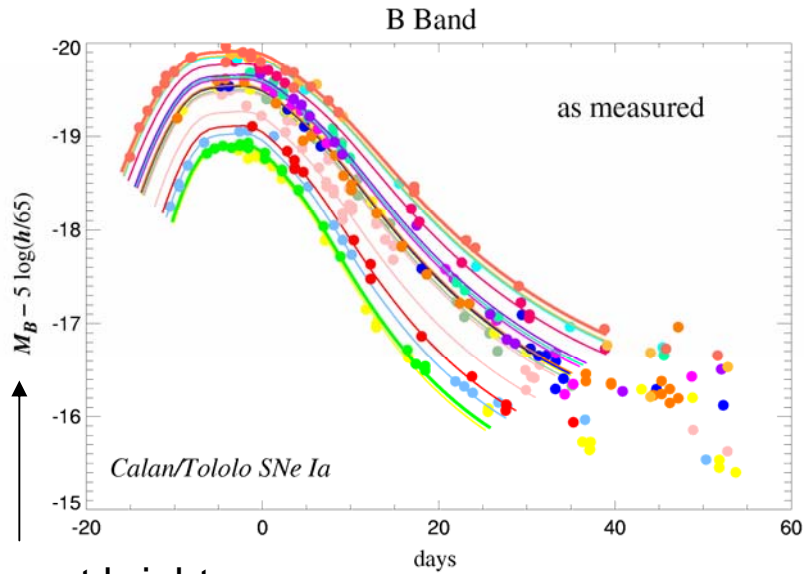
**S. Chandrasekhar**  
and his limit on the mass  
of white dwarfs

probably play a key  
role in why SNIa occur  
in nature and why they  
can be used as standard  
candles

Supernovae type Ia do not all have the same intrinsic brightness

In 1993, Mark Phillips and colleagues have shown that there is a strong correlation between peak luminosity of SNIa and the rate of luminosity decrease after the peak:

***brighter ones are slowest to fade and vice versa***



apparent brightness  
time in days with respect to peak brightness

