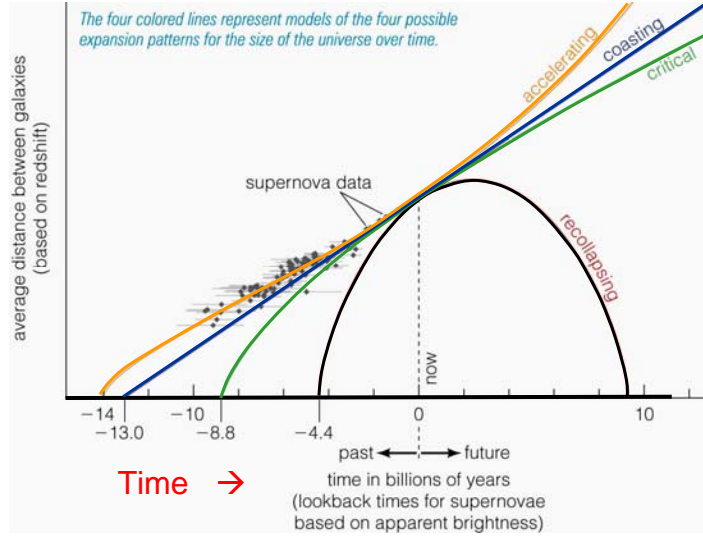


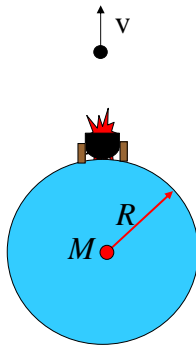
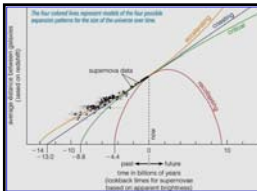
The Expansion of the Universe

[Fig. 16.16]

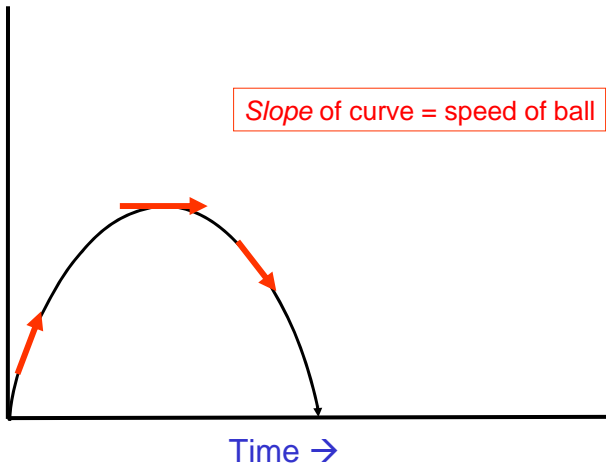
Scale Factor $R(\text{time}) \rightarrow$

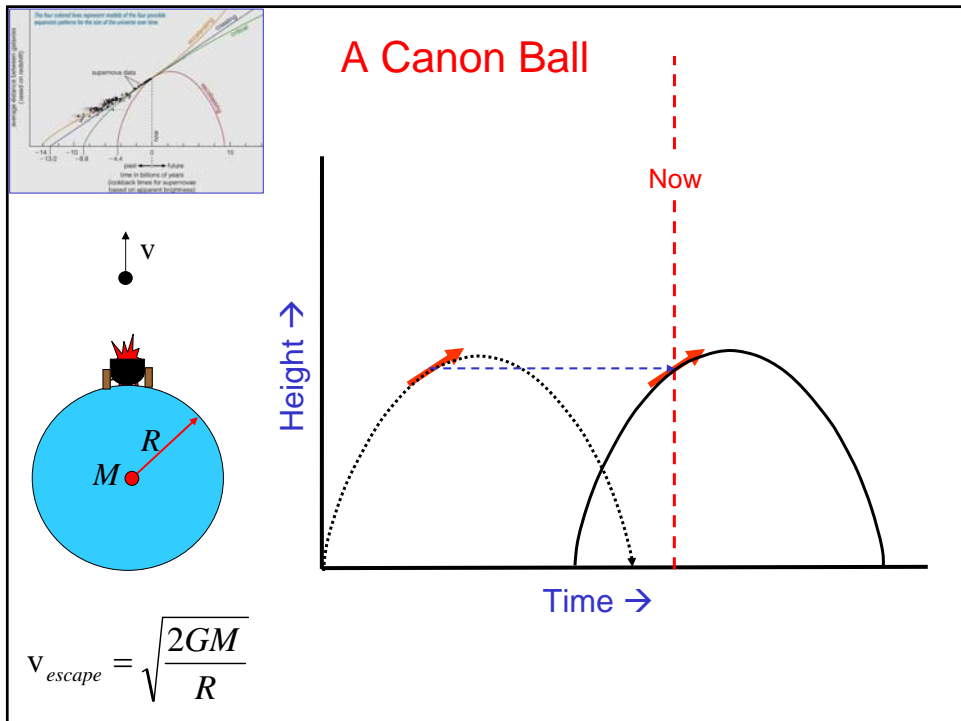
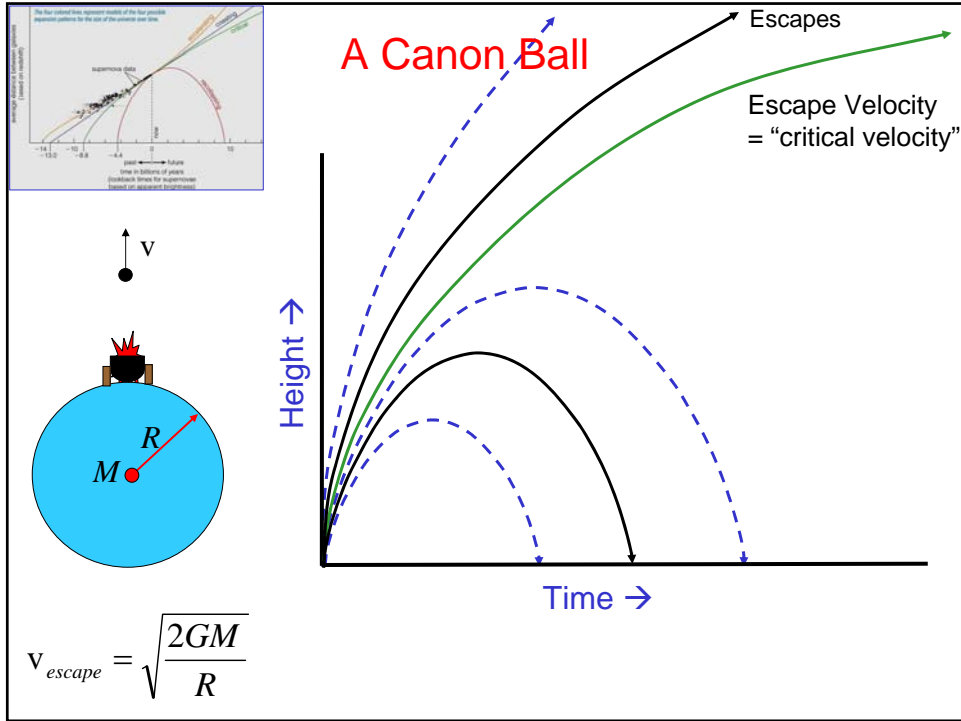


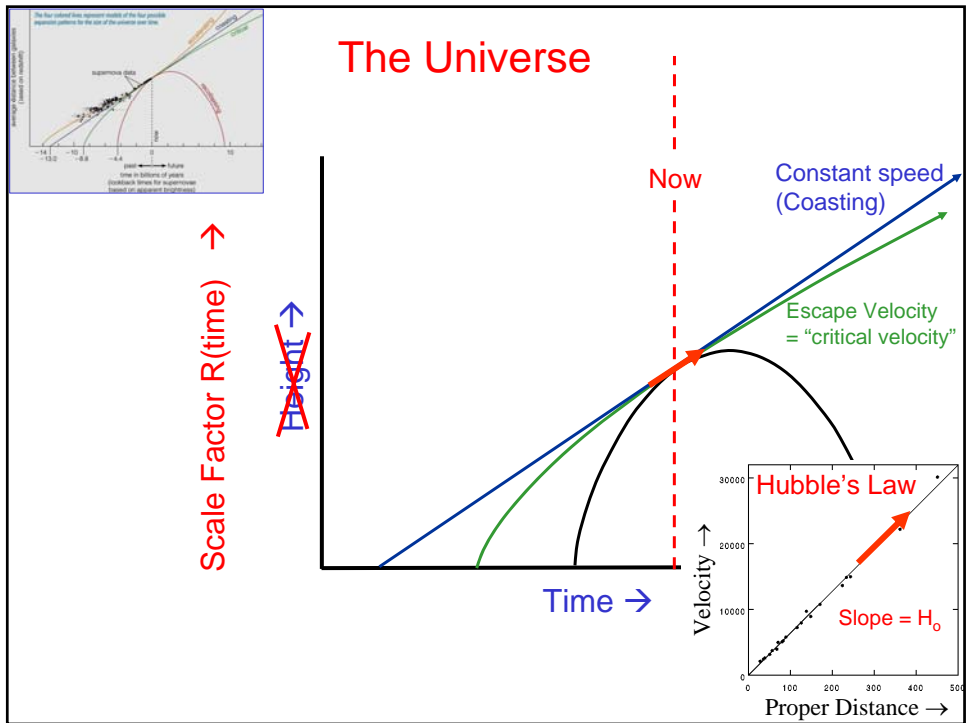
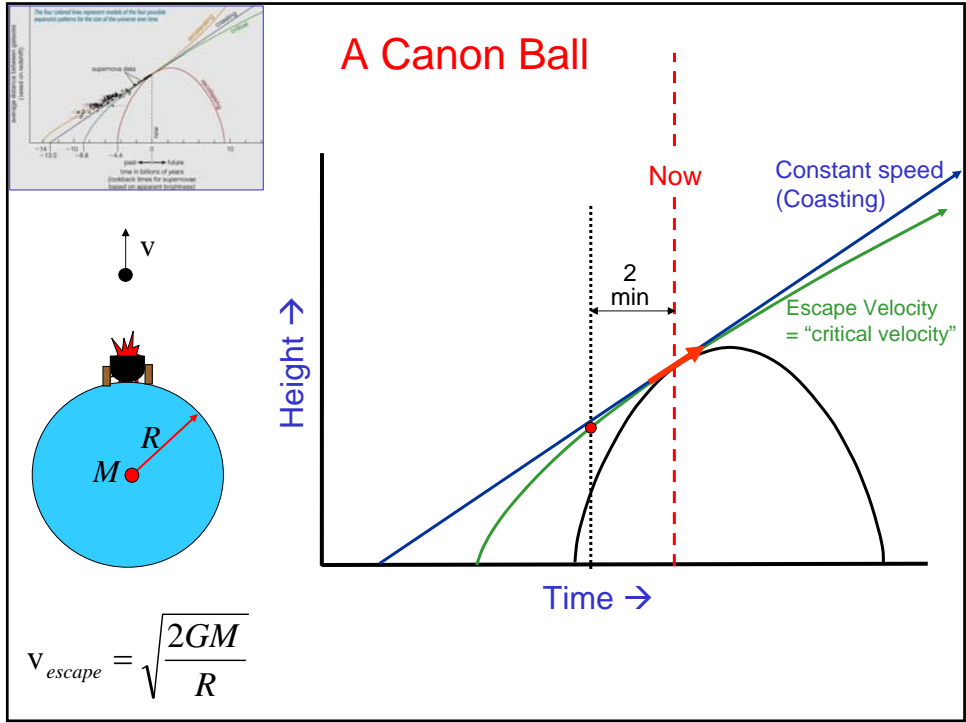
A Canon Ball

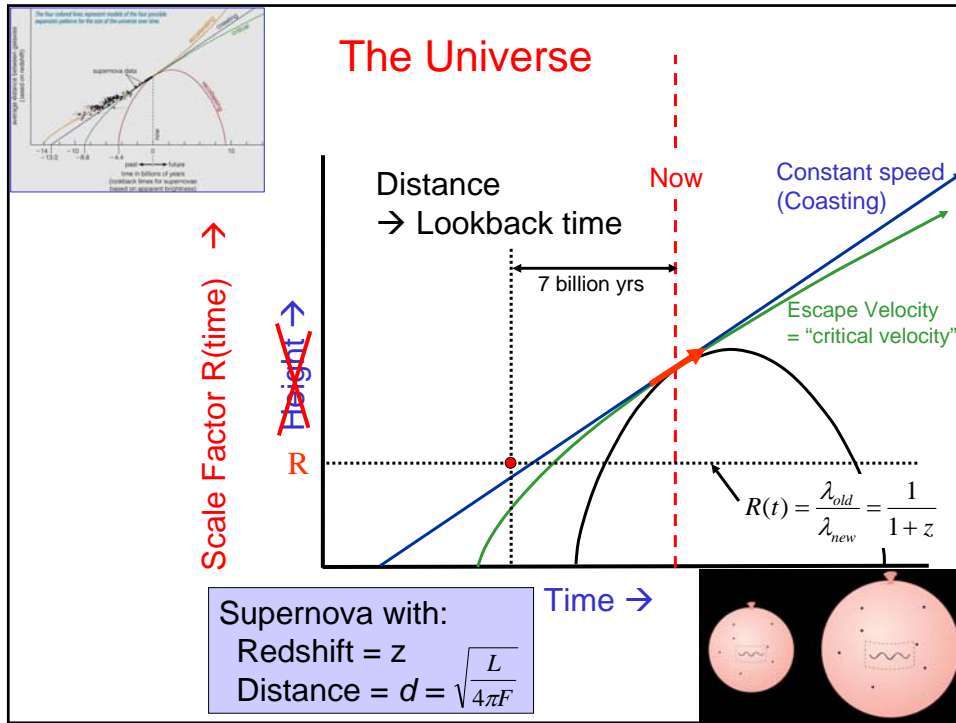


Height \uparrow








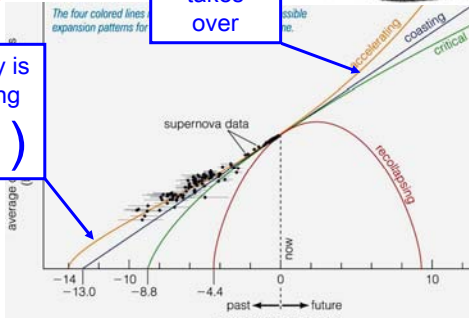


The Cosmological Constant. (Dark Energy)

- Einstein's static universe
 - Cosmological constant balanced gravity.
 - Einstein: "My greatest blunder"
- Acts as force pushing things apart.
 - Gets stronger as separation increases
- What is it?
 - Nobody knows.
- Is it really a constant?
 - Nobody knows.



Dark Energy takes over



Gravity is winning ($\frac{1}{r^2}$)

The four colored lines, expansion patterns for possible values of Λ .

accelerating

coasting

critical

recollapsing

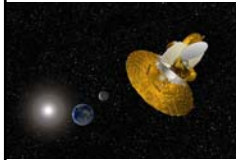
supernova data

average

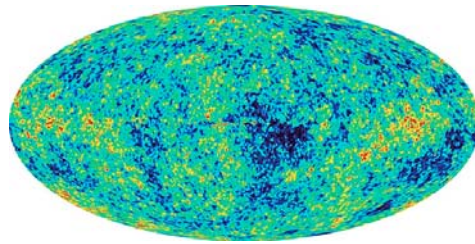
past ← → future

time in billions of years

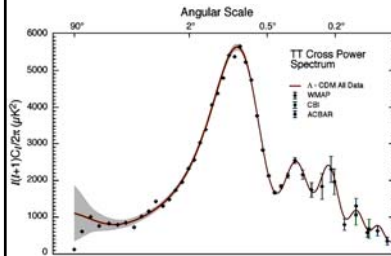
Measuring the Shape of the Universe



WMAP
Wilkinson
Microwave
Anisotropy Probe
Launched 2001

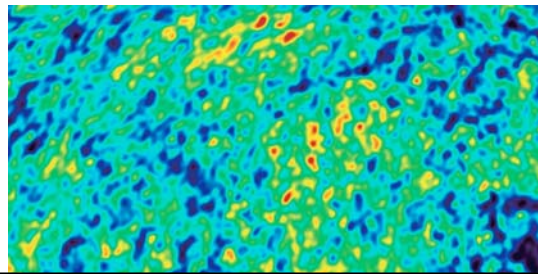


Cosmic Microwave Background map

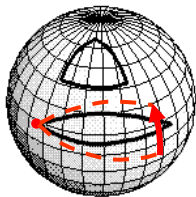


← Larger angular size

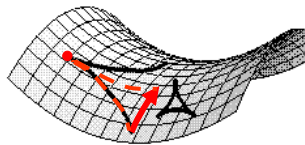
Measure amount of structure on different angular scales.



Measuring the Shape of the Universe



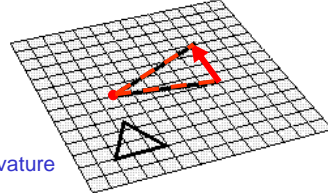
Positive Curvature



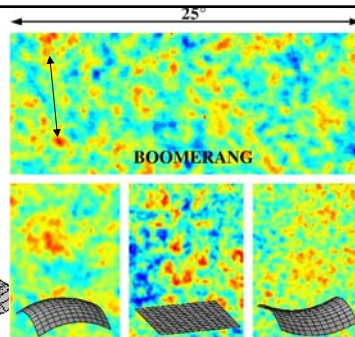
Negative Curvature

Light follows "straight" lines:

Flat Curvature



Average spacing in LY of density fluctuations is known



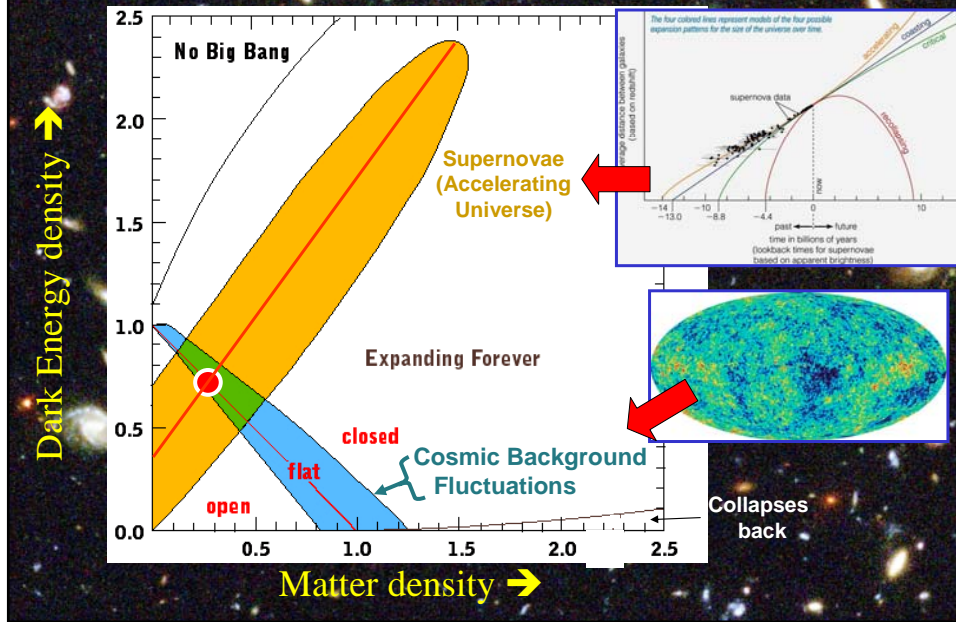
Different curvatures

→ different lensing effects

→ different angular size on sky

The Answer:
The Universe is FLAT

What is the Universe Made Of ?



What is the Universe Made Of ?

