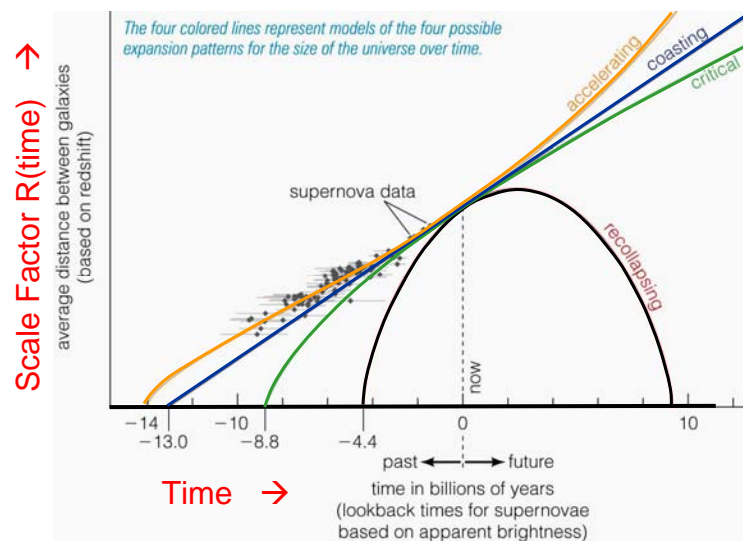


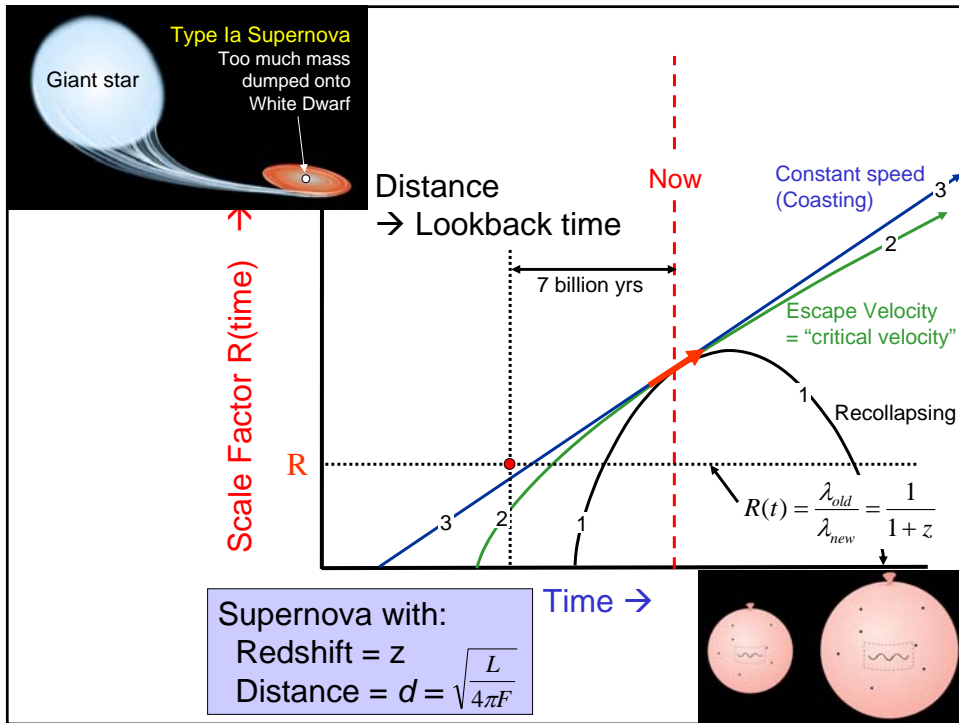
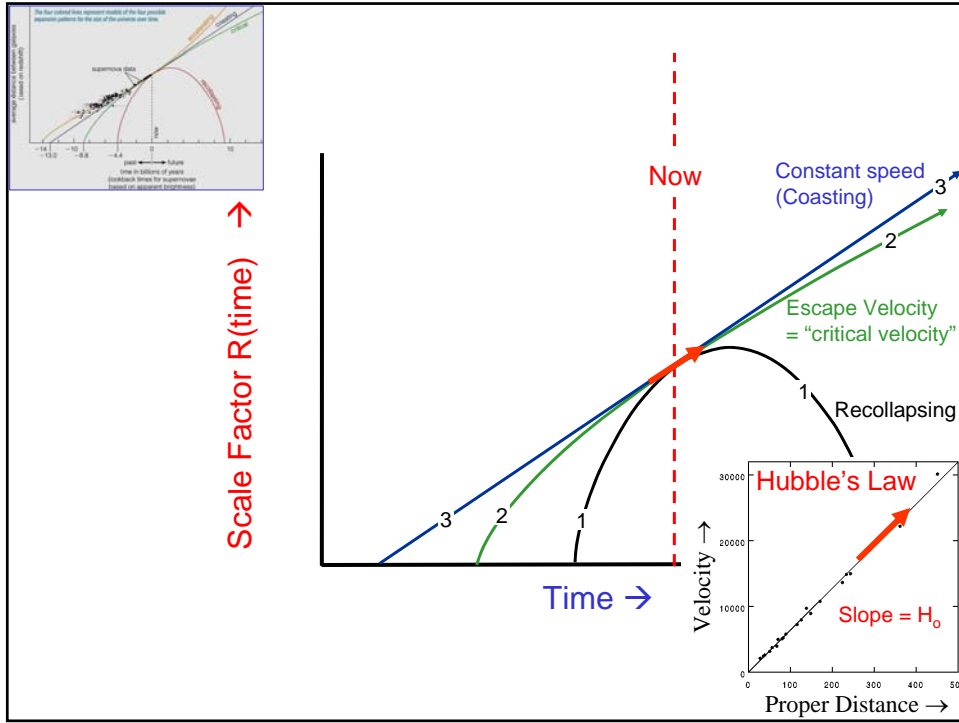
## Announcements

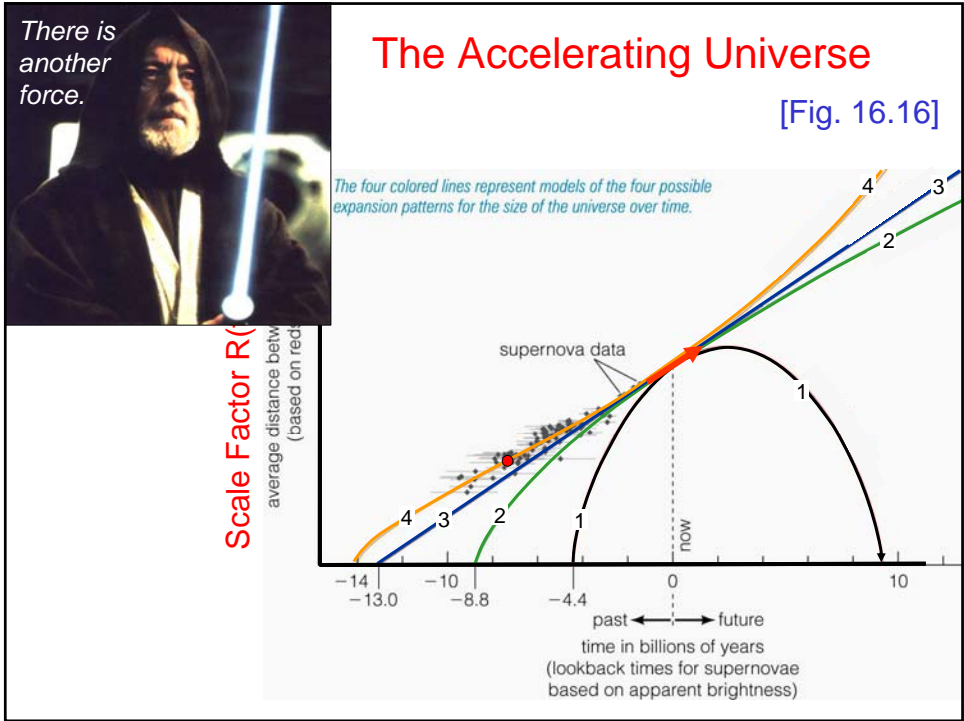
- Please.. rate this course:  
<http://rateyourclass.msu.edu>
- Study guide for final available on Wednesday.
  - + use study guides for Midterms 1-3
- Final Exam:
  - Friday May 6, 10AM - noon
  - Anthony Hall 1281.
  - 51 questions, 1/3 cumulative, 2/3 over material since Midterm 3.

## The Expansion of the Universe

[Fig. 16.16]







## 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  $(\frac{1}{r^2})$

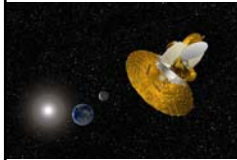
accelerating

coasting critical

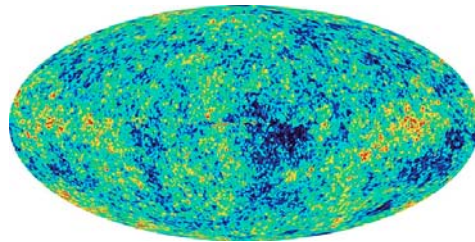
supernova data

past ← → future  
time in billions of years

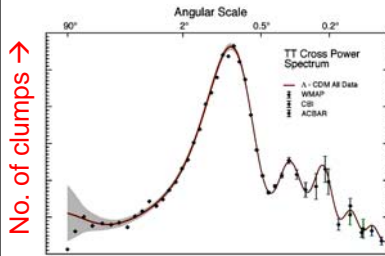
# Measuring the Shape of the Universe



WMAP  
Wilkinson  
Microwave  
Anisotropy Probe  
Launched 2001

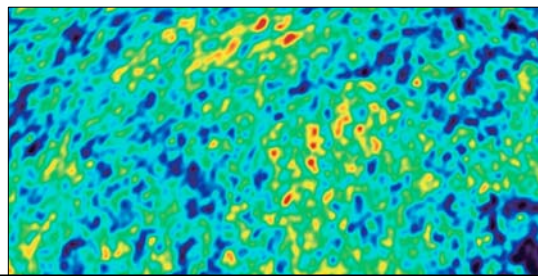


Cosmic Microwave Background map



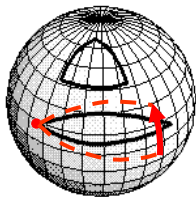
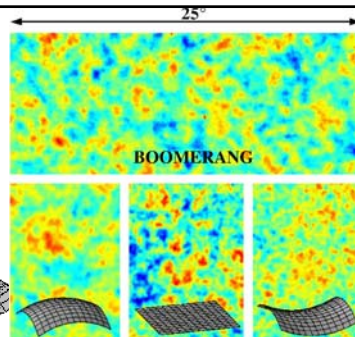
← Larger angular size

Measure amount of structure on different angular scales.

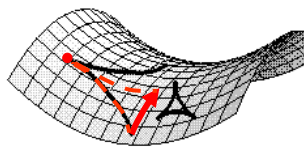


# Measuring the Shape of the Universe

Average size in LY of density fluctuations is known

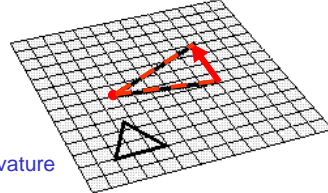


Positive Curvature



Negative Curvature

Light follows "straight" lines:

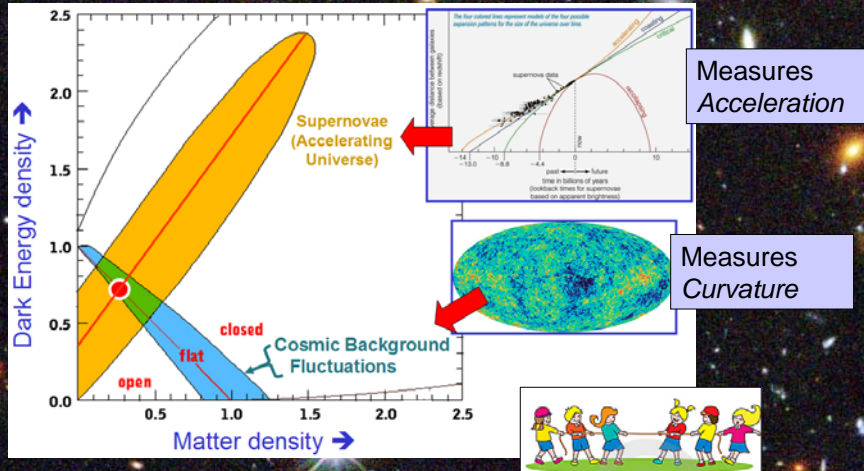


Flat Curvature

Different curvatures  
→ different lensing effects  
→ different angular size on sky

The Answer:  
*The Universe is FLAT*

# What is the Universe Made Of ?



Measures Acceleration

Measures Curvature

Acceleration = (Dark Energy) - (Matter)  
 Curvature = (Dark Energy) + (Matter)

# What is the Universe Made Of ?

*This is the only part we see.*

**4%** ~~15%~~ Normal Matter

- protons, neutrons, electrons.
- arranged into *atoms*

**23%** ~~85%~~ Dark Matter

*We infer it is there, but we don't know what it is.*

**73%** Dark Energy (using  $E = mc^2$ )