

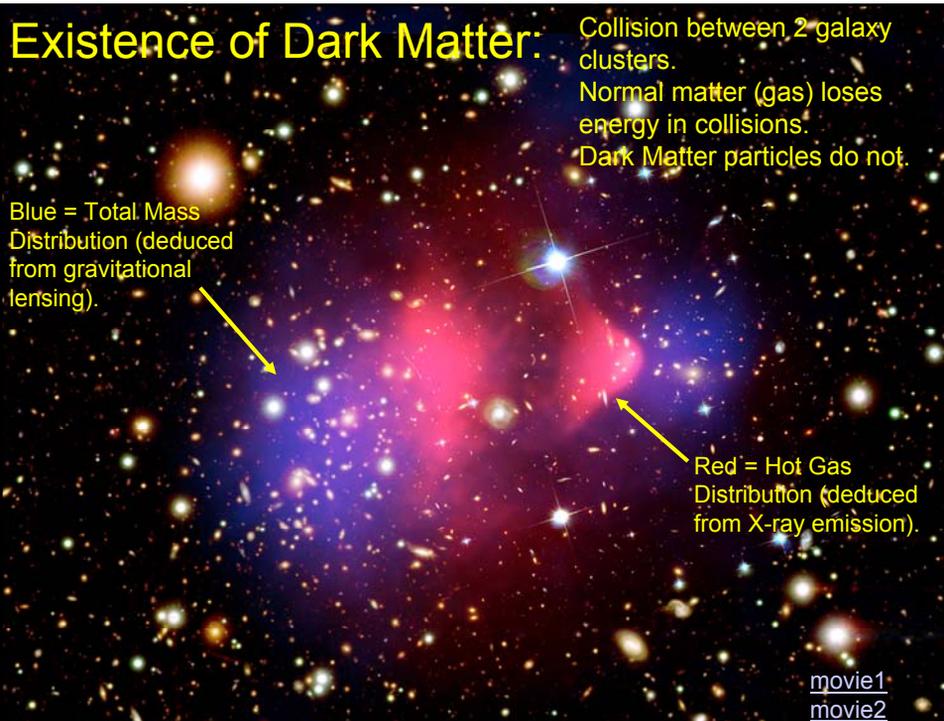
## Gravitational Lens in Galaxy Cluster Abell 2218



- Foreground cluster distorts images of numerous background galaxies.
- Use to determine total mass of foreground cluster.
- Shows that 85% of mass is Dark Matter.

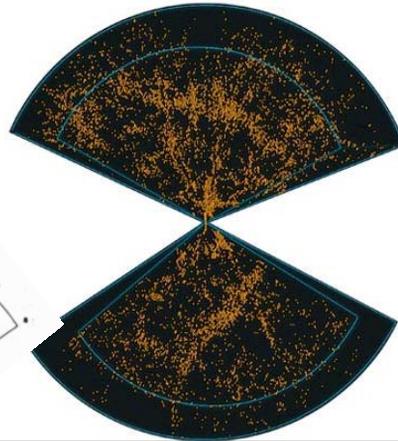
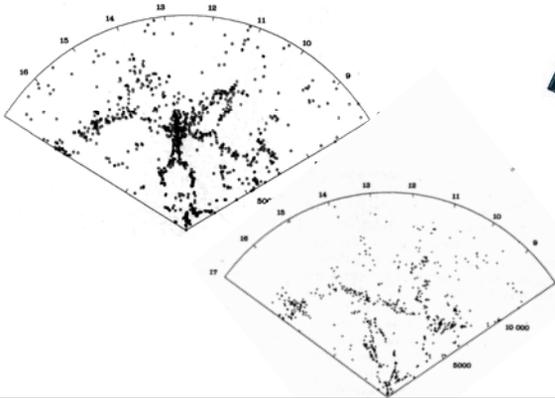
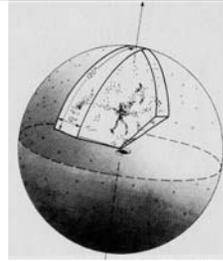
[Fig. 16.10]

## Existence of Dark Matter:



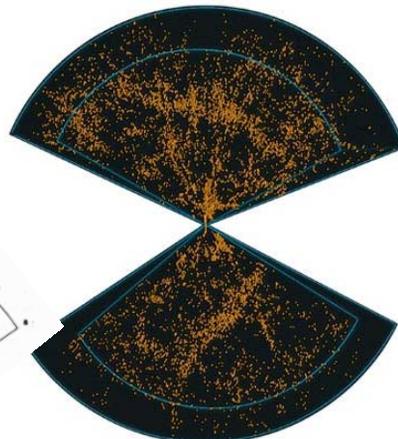
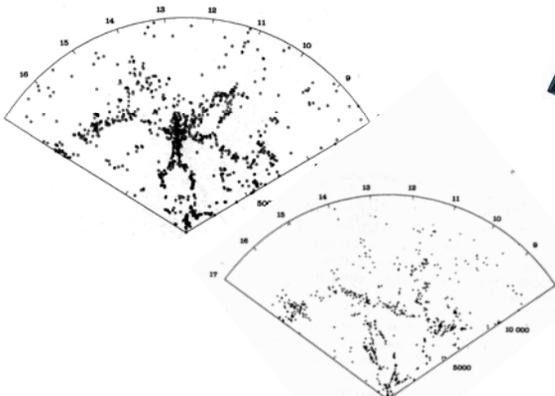
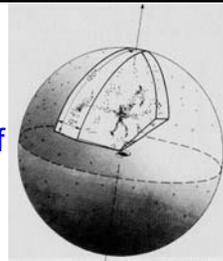
# Large-Scale Structures: A Slice of the Sky

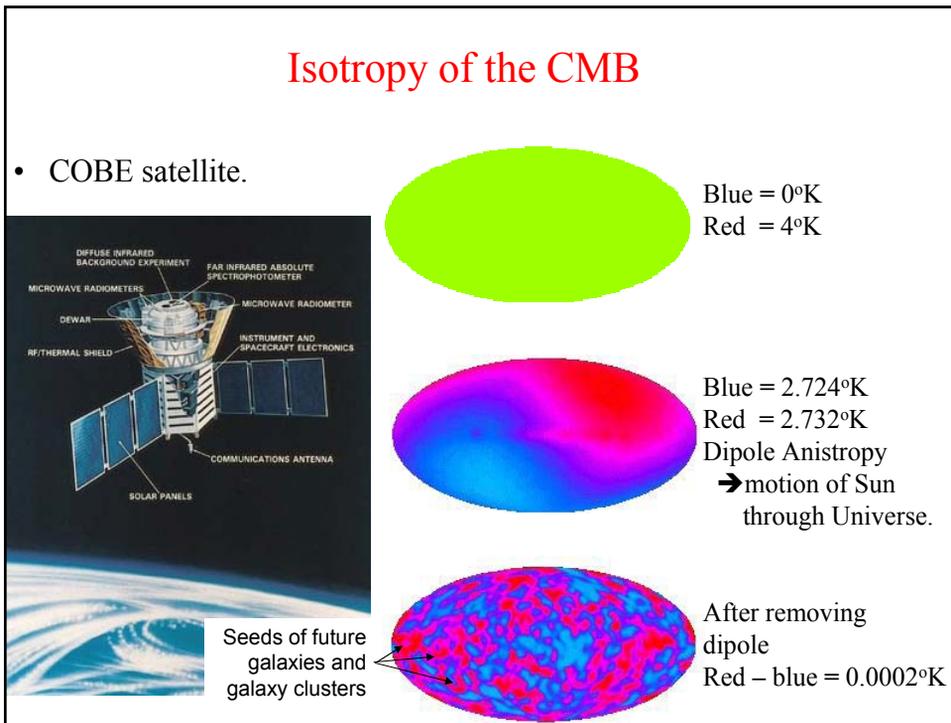
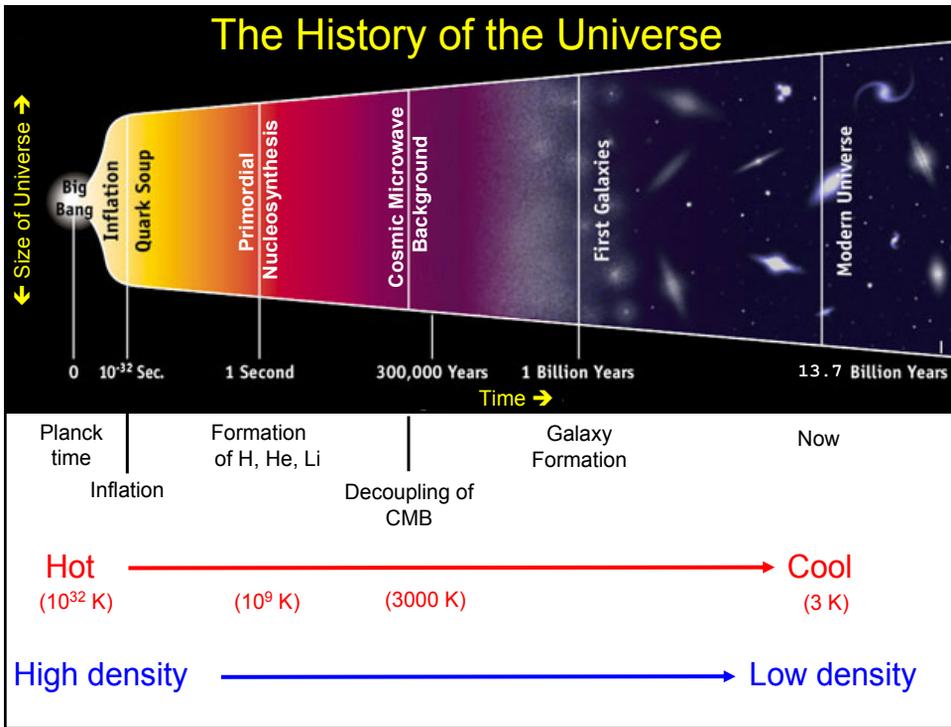
[see Fig 16.13]



Clicker question: *What sorts of 3D structures could produce 2D slices of this sort?*

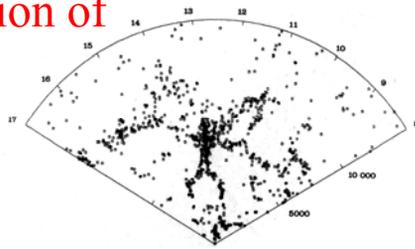
- A. Bubbles with empty interiors.
- B. Random widely-separated concentrations of matter.
- C. Spherical blobs of matter stacked close together, like pool balls before the break.
- D. None of the above.





## The Observed Distribution of Galaxies

- Like giant soap bubbles.



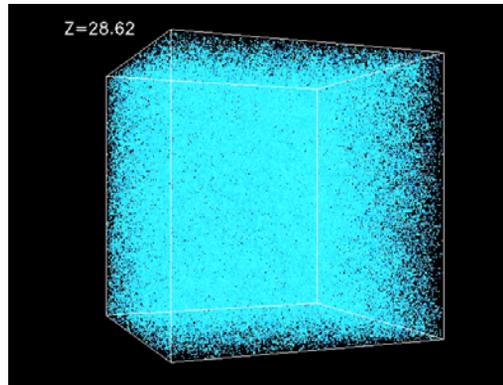
## → The Structure of the Universe

- The “Cosmic Web”.
- Structures formed due to gravitational attraction of dark matter.

The movie [NCSA](#)

Flythrough [NCSA](#)

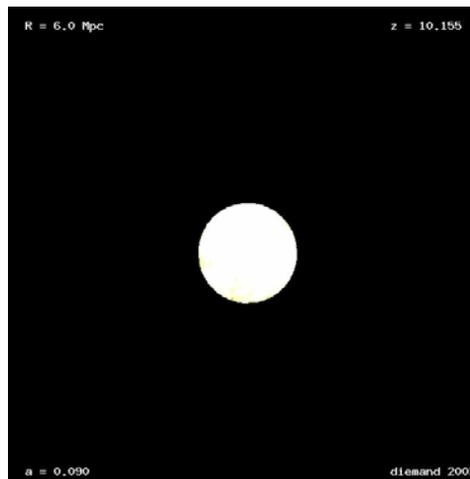
Growth of structure [NCSA](#)



In co-moving coordinates

## Same Thing in Proper Distance Units

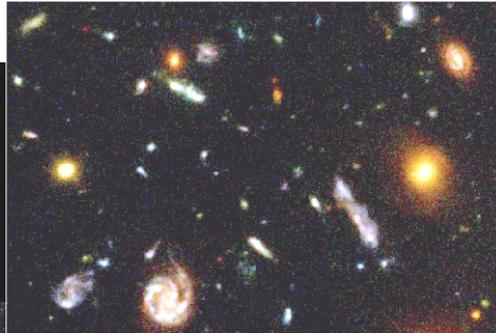
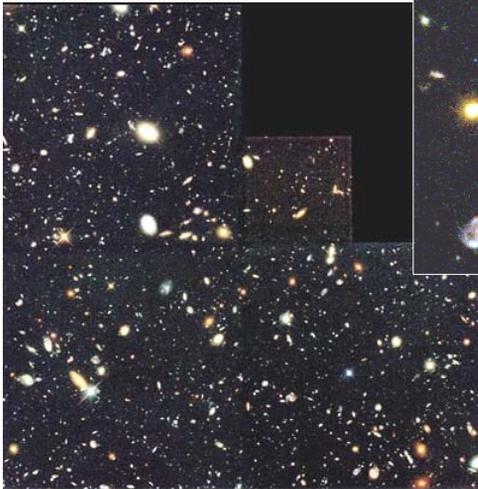
(box size is *NOT* expanding with universe)



The movie [NCSA](#)

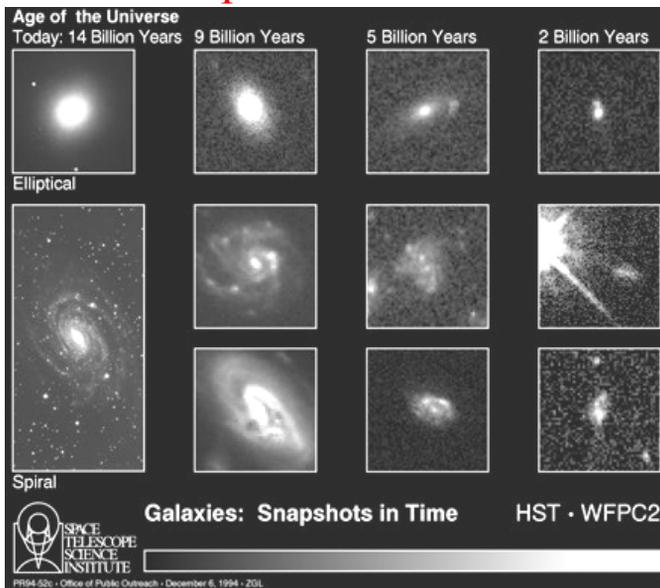
# Looking back to the time of galaxy formation

The Hubble Deep Field

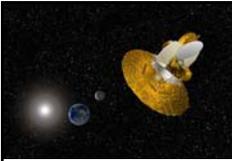


- Bottom-up structure formation.
  - We see galaxies being assembled from smaller units.
- Large galaxy clusters are still forming.

## Bottom-Up Structure Formation

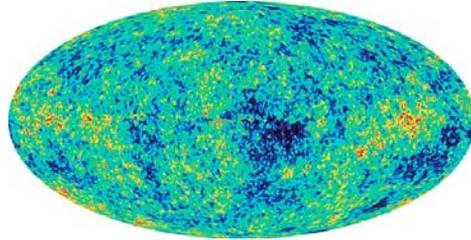


← Time

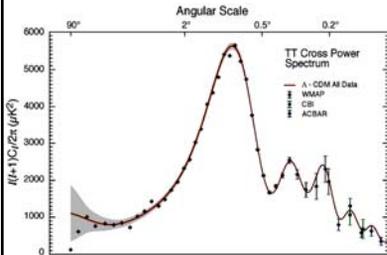


# WMAP

Wilkinson Microwave Anisotropy Probe  
Launched 2001

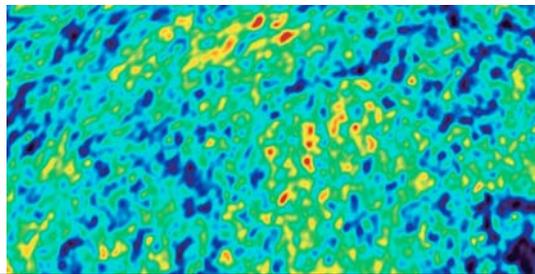


Cosmic Microwave Background map



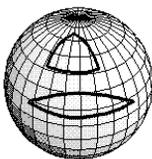
← Larger angular size

Measure “power” in fluctuations on different angular scales.

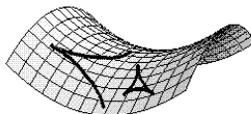


## Measuring the Shape of the Universe

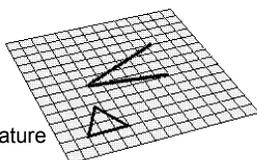
Light follows “straight” lines:



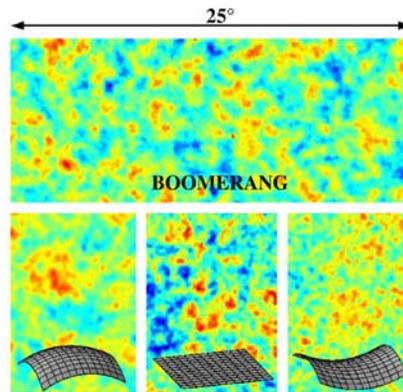
Positive Curvature



Negative Curvature



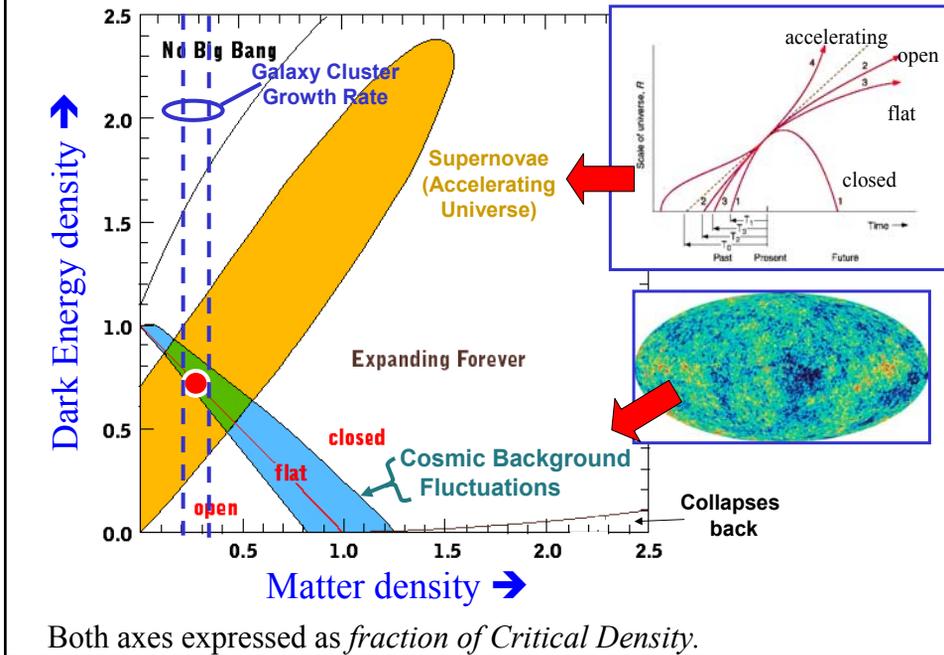
Flat Curvature



Density fluctuations have known physical size.

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

## What is the Universe Made Of ?



## What is the Universe Made Of ?

73% Dark Energy  
 23% Dark Matter  
 4% Normal Matter

*We infer these are there, but we don't know what they are.*

(using  $E = mc^2$ )

*This is the only part we see.*

## MSU's SOAR Telescope



- Is there life elsewhere?
- The history of the universe.
  - The first stars.
  - Evolution of galaxies.
- What is dark matter?
- What is dark energy?

*Some BIG questions for  
astronomy:*

# Announcements

My Office Hours  
(BPS 3270)  
3-4 Mo, 2:30-3:30 Tu,  
4-5 Fri

- **Homework 8**  
Due late at night Friday April 27 (6:30AM Apr 28)
- **Final exam info**
  - 8-10PM Thursday May 3 in Natural Resources 158
    - SW corner of Farm Lane & Wilson
  - About 50-55 questions.
  - About half on material since Midterm 3 (including my lecture on March 29)
    - Questions provided by Prof. Smith & Baldwin
      - I will only ask about material in lectures or on homework.
      - Sample questions at [www.pa.msu.edu/courses/isp205/sec-1](http://www.pa.msu.edu/courses/isp205/sec-1)
    - Study guide coming on Wednesday
  - About half on material up through Midterm 3
    - Questions provided by Prof. Loh
    - Use same study guides as for midterms
      - already available on syllabus page on Angel

Please rate this course at <http://rateyourclass.msu.edu>