

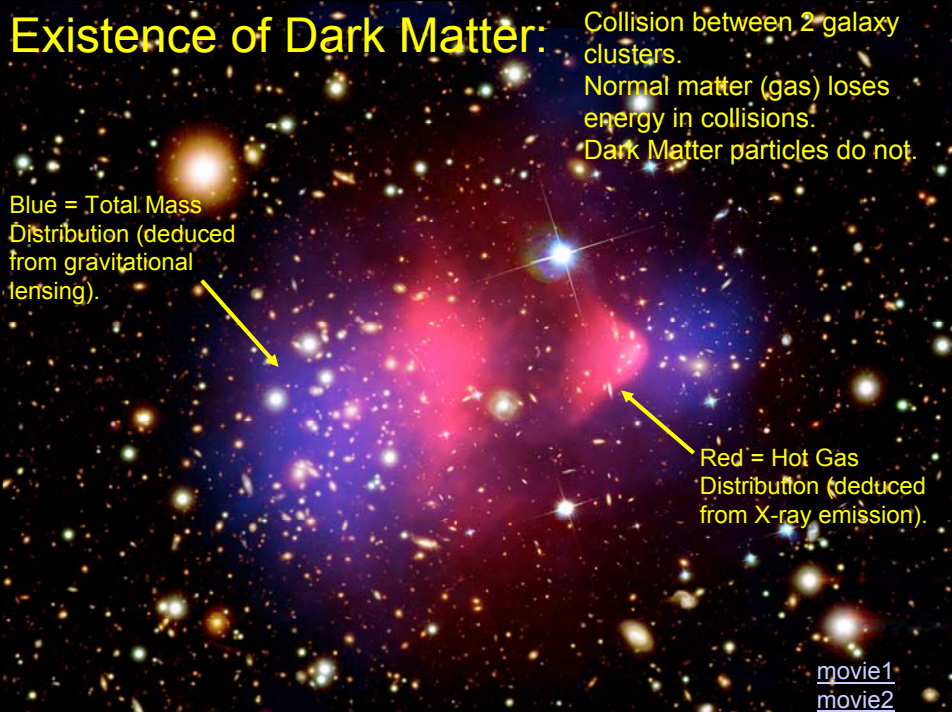
Gravitational Lens in Galaxy Cluster Abell 2218



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

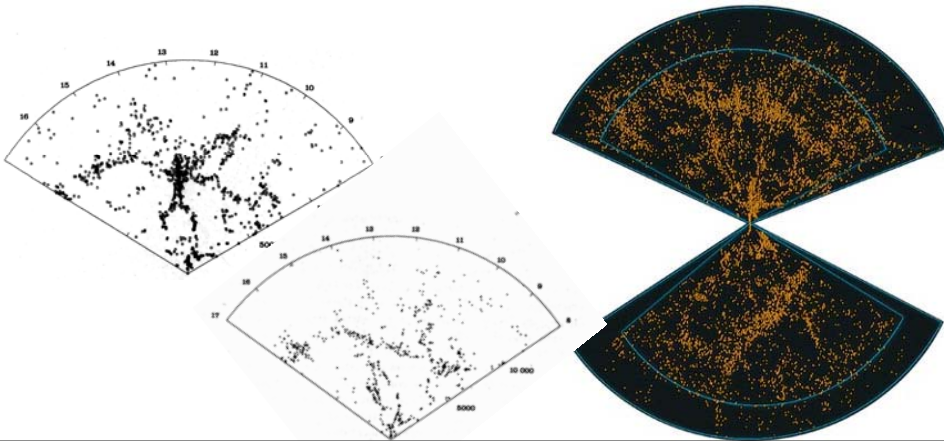
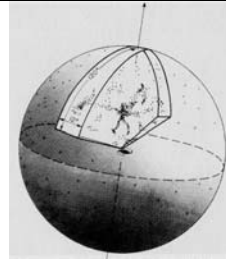
[Fig. 16.10]

Existence of Dark Matter:



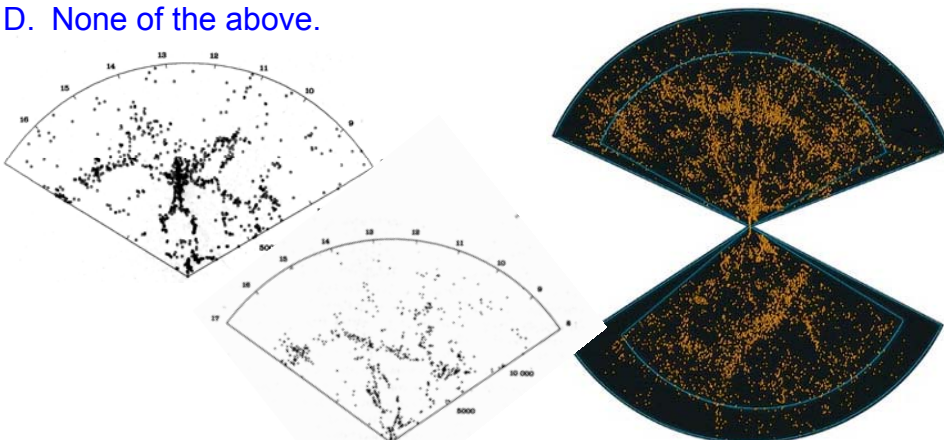
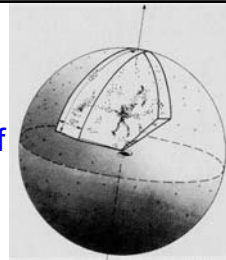
Large-Scale Structures: A Slice of the Sky

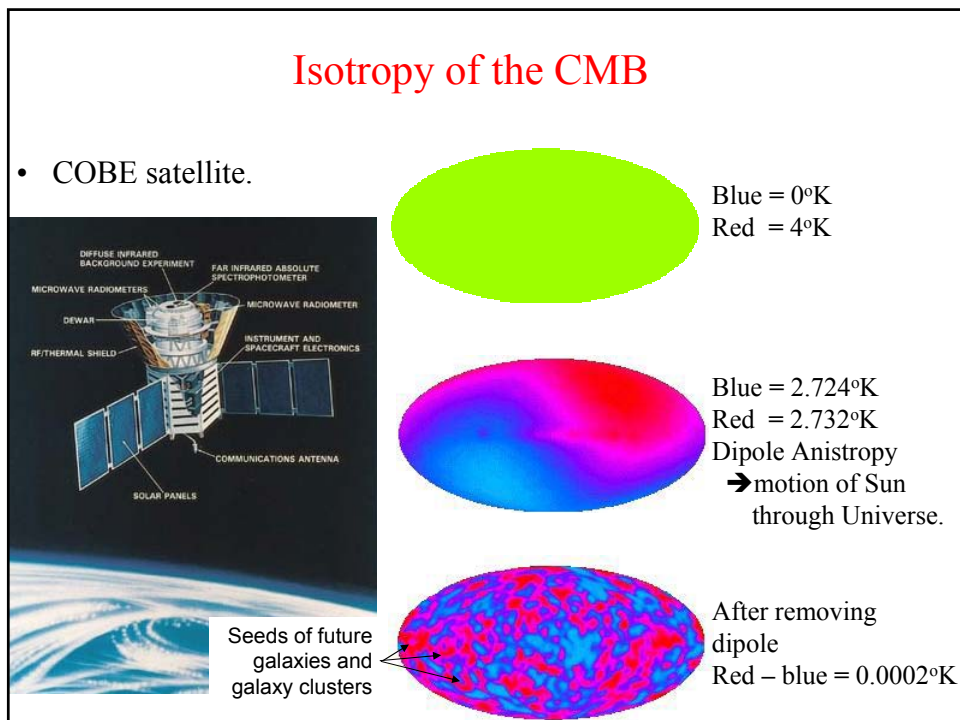
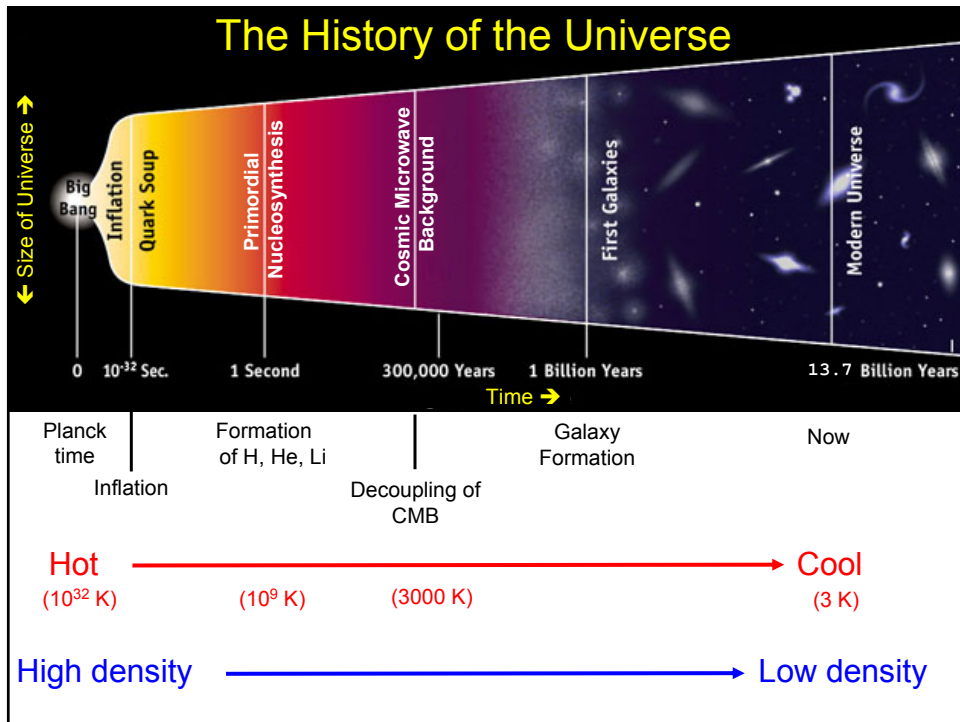
[see Fig 16.13]



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

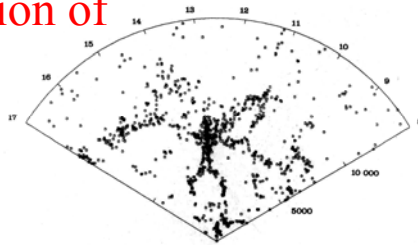
- A. Bubbles with empty interiors.
- B. Random widely-separated concentrations of matter.
- C. Spherical blobs of matter stacked close together, like pool balls before the break.
- D. None of the above.





The Observed Distribution of Galaxies

- Like giant soap bubbles.



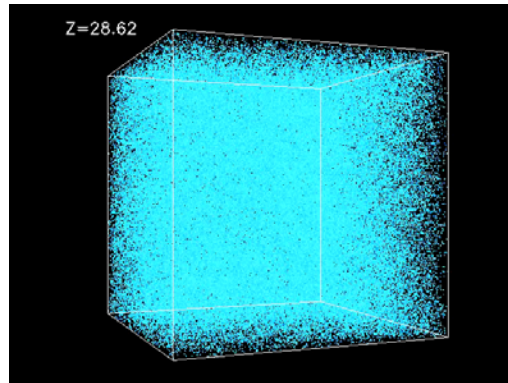
→ The Structure of the Universe

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

The movie [NCSA](#)

Flythrough [NCSA](#)

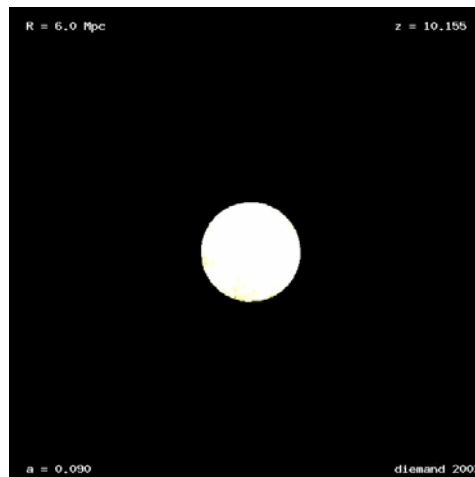
Growth of structure [NCSA](#)



In co-moving coordinates

Same Thing in Proper Distance Units

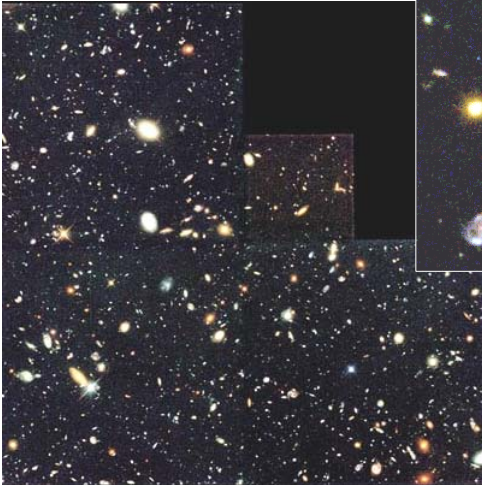
(box size is *NOT* expanding with universe)



The movie [NCSA](#)

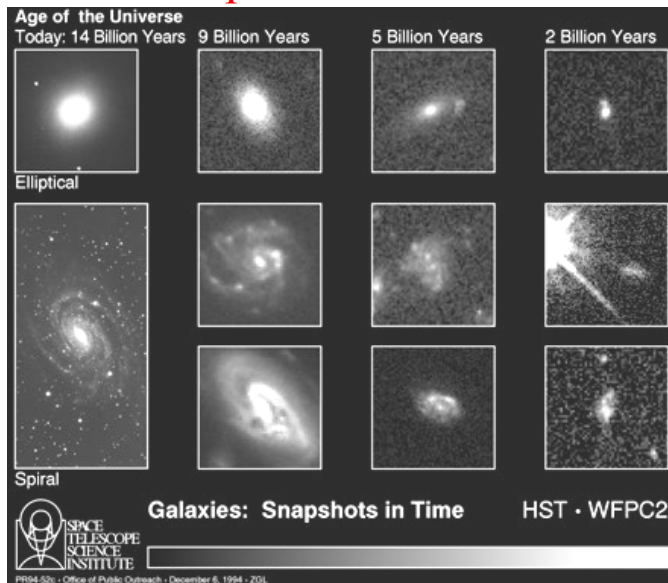
Looking back to the time of galaxy formation

The Hubble Deep Field

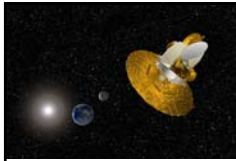


- Bottom-up structure formation.
 - We see galaxies being assembled from smaller units.
- Large galaxy clusters are still forming.

Bottom-Up Structure Formation

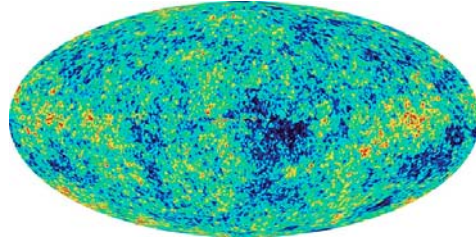


← Time

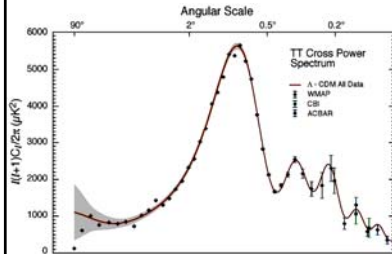


WMAP

Wilkinson Microwave Anisotropy Probe
Launched 2001

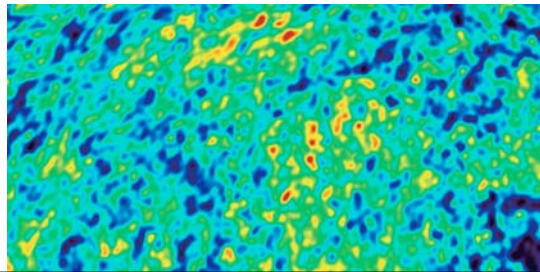


Cosmic Microwave Background map



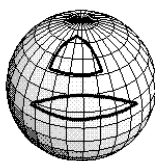
← Larger angular size

Measure “power” in
fluctuations on
different angular scales.

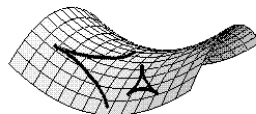


Measuring the Shape of the Universe

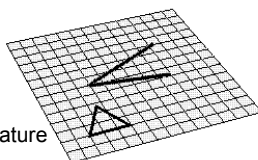
Light follows
“straight” lines:



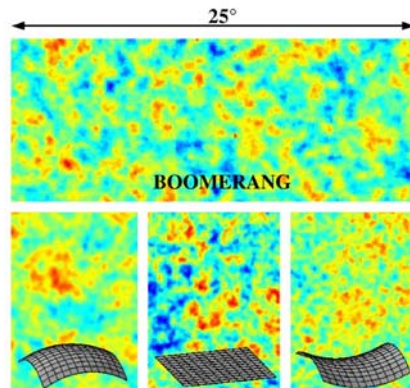
Positive
Curvature



Negative
Curvature



Flat
Curvature



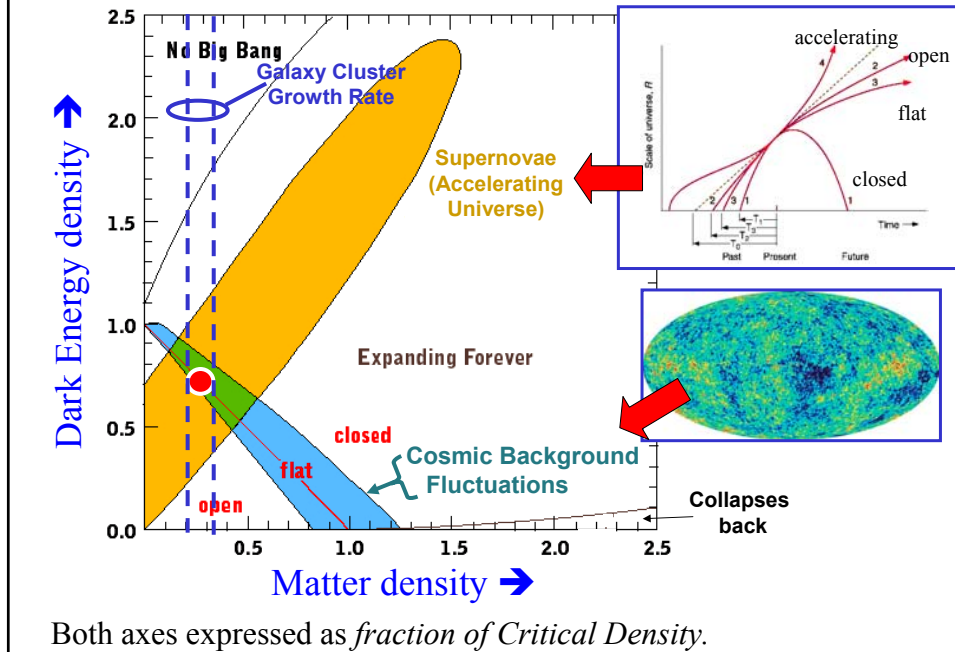
Density fluctuations have
known physical size.

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

(using $E = mc^2$)

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

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
 - 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>