Dark Matter Structure of the Universe

Group worksheet:

group members

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Introduction:

Physicists and astronomers have amassed an enormous amount of evidence that supports the scientific theory — the Big Bang theory —that the Universe began 13.7 billion years ago in a state that was extremely hot, almost infinitely dense, and incomprehensibly small. Obviously the Universe today is cool, diffuse, and large. But how did the Universe get this way, considering that its beginning was the extreme opposite of its condition today? If the Big Bang theory does not provide tests to answer this question, then it is useless as a scientific theory and must be discarded. In this lab we will examine how the Universe became large, and why its density changed over billions of years. The Big Bang theory is explored mathematically, in part, by recasting it in the form of computer simulations. If the simulations do not correspond to astronomical observations, the theory will be proved wrong.

Expansion of the Universe in 2-Dimensions:
Goals: - Understand how the Universe expands

Dark Matter in 2-Dimensions:
Goals: - Understand co-moving distances
- Differentiate Cold and Hot dark matter in 2D simulations

Dark Matter in 3-Dimensions:
Goals: - Differentiate Cold and Hot dark matter in 3D simulations
- Compare simulations to data

Expansion of the Universe in 2-Dimensions

A central hypothesis of the big bang theory is that the Universe was microscopically small 13.7 billion years ago. Because it is much, much larger now, a reasonable conclusion is that the Universe has expanded considerably during its existence. To get an idea of how expansion works, observe the simulation at the website

http://physics.scsu.edu/~dms/cosmology/2D_hubble_law.html

The big black circle represents the entire expanding Universe, and each yellow spot with a number represents a galaxy, an aggregation of 100 billion stars. A yellow spot with no arms represents an elliptical galaxy , while a yellow spot with arms represents a spiral galaxy. (Galaxies can also have no particular shape at all, called irregular.)

Place the cursor on the spiral galaxy labeled with number 5 in the lower right portion of the expanding universe (black circle) that's at the top of the web page. Notice that all of the other galaxies are moving away from galaxy 5. This is what the astronomers of galaxy 5 would observe. Now scroll down to the second expanding universe, and place your cursor on spiral galaxy labeled with number 46, just above the center, slightly left. Notice that all of the other galaxies move away from galaxy 46; this is what astronomers in galaxy 46 would observe.

Question 1. If an astronomer lives in any one of the other galaxies, what do you expect that astronomer to observe about all of the other galaxies?

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Question 2. Would the inhabitants of any one of the galaxies be able to claim that they were at the center of the universe because all of the other galaxies are moving away?

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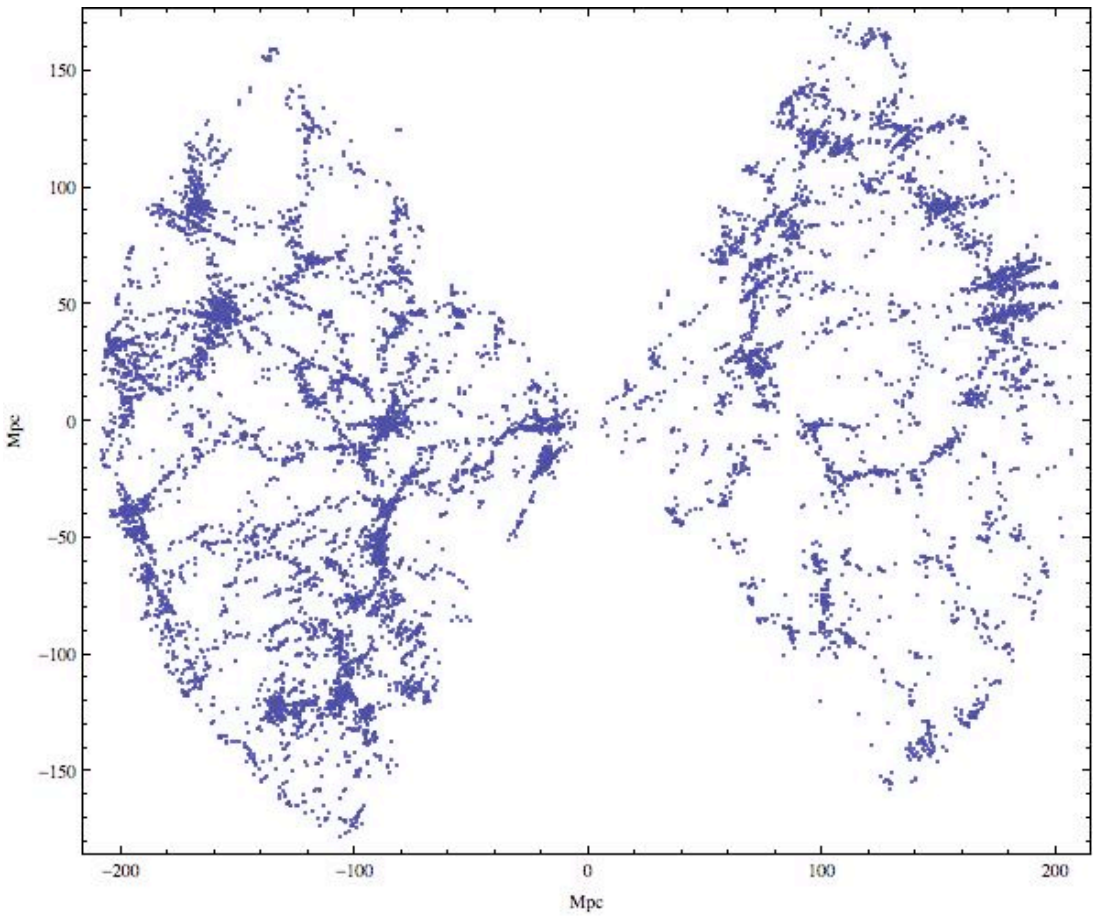
Now examine the plot below of 9,660 actual galaxies (from the Sloan Digital Sky Survey, SDSS) observed by earth-based astronomers. Each dot represents a galaxy, either a spiral, an elliptical, or irregular.



150
100
50
0
−50
−100
−150
Mpc
−200
−100
0
100
200
Mpc

(The earth is at the point where the two wedges meet; gas and dust prevent astronomers from seeing the galaxies in the empty wedges of the "pie.")

Question 3. How does the arrangement of the galaxies in the plot above differ from the arrangement of the expanding galaxies that you observed on the web, ignoring the obvious size differences and the web animation?

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Notice that the expanding web galaxies were not shown to cluster, but the real galaxies plotted above do cluster because of gravitational attraction. But is all clustering alike? Are there different kinds of clustering? In the next section of this lab we will see that the amount of clustering depends upon what kind of matter causes the clustering in the first place.

Physicists and astronomers have determined that the galaxies did not form first, then cluster. The gas of which the galaxies are made clustered about another form of matter first before stars were formed and galaxies were created. The matter that attracted the gases initially is called *dark matter* because it is impossible to see, and nobody knows what it is.

Dark Matter in 2-Dimensions

You will explore dark matter in a 2-dimensional universe, before working in 3-dimensions. First, the expansion will be represented in a simpler way than before, with the expanding black circle. Then you will observe how changing the fraction of matter in the 2-D universe affects clustering. And the last 2-D exploration will reveal the difference between two types of dark matter — hot and cold.

Comoving Distance

Open the file 2D_Dark_Matter_ClusterGrowth.nbp, the 2-D dark matter simulator, in the *CDF Player* application. Choose parameters as follows: angularSize=32, expansionTime=4, fractionFilled=0.09, and coldHot=1. Now click on the Expand Universe button and wait until four frames appear.

Question 4. What do you notice about the dark matter when you compare the 1st frame to the 3rd frame?

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Question 5. What do you notice about the dark matter clusters when you compare the 3rd frame to the 4th frame?

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You should observe clustering in going from the 1st frame (early in the Universe) to the 3rd frame (later in the Universe). What you should observe when comparing the 3rd frame with the 4th frame (even later in the Universe) is that the dark matter clusters move away from each other, even though the frame containing all of the clusters remains the same size. For the rest of this lab, expansion of the Universe will be represented in this way. Astronomers call this method of describing the expansion as using the *comoving* frame.

Question 6. Suppose that you used a "ruler" to measure a distance of 50 Mpc between two dark matter clusters and the "ruler" expanded along with the rest of the Universe. What would be the measured distance between the two dark matter clusters at a later time according to the "ruler"?

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The comoving distance between the two clusters would not change from 50 Mpc. Of course the actual distance between the clusters is increasing because the Universe is expanding, so using the comoving frame is a matter of convenience: Showing the actual expansion would fill up the entire screen or more.

***Fraction of Dark Matter* in the *2D* Universe**

You will now explore how the fraction of dark matter in the Universe affects the number of the clusters in the Universe. Quit the 2-D dark matter simulator, then reopen it to get a fresh screen. To discover what happens to the dark matter clustering as the fraction of dark matter in the Universe (controlled by fractionFilled) is increased, begin with angularSize=32, expansionTime=4, fractionFilled=0.1, and coldHot=1. Click on the "Expand Universe" button, wait until four frames appear, then count the number of clusters in the last frame and record in the table below. *Without any changes* repeat this procedure four times and record in the table below. Find the average number of clusters.

Run Number (fraction = 0.1)	**Number of Clusters**
1	
2	
3	
4	
5	
Average	

Again, quit the 2-D dark matter simulator, then reopen it to get a fresh screen. Continue with angularSize=32, expansionTime=4, fractionFilled=0.2, and coldHot=1 to complete the table below. Find the average number of clusters.

Run Number (fraction = 0.2)	**Number of Clusters**
1	
2	
3	
4	
5	
Average	

Question 7. Look at the galaxies plotted on page 3, and notice that there are many clusters, both large and small. From what you've observed by running the simulations, and assuming that the 3rd frame of the simulations has the same scale as the galaxy plot, which dark matter fraction do you suppose is most likely to cause the *galaxies* to clump, 0.1 or 0.2? Briefly explain your reasoning

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You have just experienced with a simplified model of dark matter a process similar to what cosmologists experience when they try to determine how much dark matter there is in the universe. If the fraction filled parameter could not be adjusted to resemble the actual universe, then the dark matter hypothesis would be discarded.

Hot and Cold Dark Matter in 2-D

Although all that is known for certain about dark matter is that it creates a gravitational field, just like all other matter, physicists can test other ideas about dark matter. Is the dark matter very energetic (hot) so that its particles move about at a high speed, or is it not very energetic at all (cold) so that dark matter particles are barely in motion? You will try to answer this question using simulations, just as physicists do, because experiments cannot be performed with actual dark matter particles.

Quit the 2-D dark matter simulator, then reopen it to get a fresh screen. Set the values at angularSize=32, expansionTime=3, and fractionFilled=0.15. Click the "Compare Cold-Hot Dark Matter" button (coldHot has default values set for the comparison) and wait for the three frames to appear. Note that the cold and hot dark matter start with exactly the same configuration initially. Now measure the distance, to the nearest tenth of a centimeter, across the largest cluster in the third frame, for the cold dark matter (on the left) and for the hot dark matter (on the right) and record the values in the table below. *Without any changes* repeat this procedure four times and record in the table below. Find the average cluster size in each case.

Run Number	**Cluster Size (cm) (coldHot=1)**	**Cluster Size (cm) (coldHot=8)**
1		
2		
3		
4		
5		
Average		

Question 8. Based on the average of your measurements, what kind of dark matter, cold or hot, results in the largest clusters?

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The significance of your answer to question 8 will not be apparent until you try to match the dark matter simulations in 3D to the galaxy data in 3D.

Dark Matter in 3-Dimensions

Open the file Galaxies_SDSS_zLT03.nb, a plot of 70,925 galaxies from the Sloan Digital Sky Survey (SDSS). Use your mouse to rotate the plot, paying close attention to the pattern formed by the galaxies within the wedge. Notice that there are spaces (voids) where there are no galaxies; also notice the size of the galaxy clusters.

Now open the file 3D_Dark_Matter_ClusterGrowth.nbp to see what dark matter structure is most likely to give rise to the galaxy structure. Set the simulator values equal to those used to explore cold dark matter in 2-dimensions: angularSize=32, expansionTime=3, fractionFilled=0.15, and depth=8, then run the simulation by clicking on “Compare Cold-Hot Dark Matter.” Expand the window so that you see two plots side by side. Use your mouse to flip the third box, for hot and cold, to get a top view. Repeat at least three times to get a good idea about which simulation (hot or cold) is more like the actual galaxy distribution

Question 9. Which of the dark matter simulations, cold or hot, seems to you most likely to cause the SDSS galaxy plot? Also, use your result from Question 8 to help answer this question. Justify your answer.

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