# Unit 10

# Dark Matter

## Introduction

> *The Universe is made mostly of dark matter and dark energy, and we don't know what either of them is.*
> – Saul Perlmutter, astrophysicist

In Units 1 and 2, we explored the most basic constituents of the universe—quarks, electrons, neutrinos, bosons, and the exotic particles created in accelerators. In this unit we learn about *dark matter* that, along with *dark energy* (the topic of the next unit), makes up 96% of the matter and energy in the universe. Several lines of evidence from diverse fields point to the existence of dark matter, but scientists are still unsure of the nature of this mysterious substance and it has yet to be observed directly. We know that it exists, but don't know what it is. The quest to observe and characterize dark matter is a major focus of both particle physics and astrophysics.

### *What Will Participants Learn?*

Participants will be able to:

1. Compare and contrast dark matter with normal matter in terms of its basic properties and distribution in the universe.
2. Describe at least the following two of the lines of evidence for the existence of dark matter.
    a. Describe the relationship between orbital radius and velocity for bodies in the solar system and compare to that of stars orbiting in galaxies.
    b. Describe the effects of gravity on light traveling from distant places in the universe and compare "gravitational lenses" to traditional optical lenses.
3. Explain how two principles of the nature of science, *Evidence* and *Coherence & Consistency*, justify scientists' claim for the existence of dark matter based on data and evidence from multiple fields.

### *What's in this Unit?*

**Text:** Unit 10: *Dark Matter* outlines the evidence for the existence of dark matter, including *galaxy cluster rotation* (Zwicky), simulations of the development of galaxies over time (Ostriker and Peebles), rotation of stars around galaxies (Ford and Rubin), the fluctuations in the *cosmic microwave background (CMB)*, and the synthesis of elements in the Big Bang. Alternative hypotheses (such as *modified Newtonian dynamics (MOND)* are discussed. The text also explores the search for the particles that make up dark matter—in particular, *axions*, *weakly interacting massive particles* (*WIMPs)*, and *massive compact halo objects* (*MACHOs)*. What is the nature of these hypothesized particles and objects, and what data would provide evidence for their existence?

**Video:** The program examines the research of two scientists who are searching for dark matter in two different directions. Doug Finkbeiner of the Harvard-Smithsonian Center for Astrophysics is exploring the cosmos, examining CMB radiation. The glow from the

Big Bang has been redshifted such that astronomers observe it not as visible light, but as a microwave "glow". In order to see this background radiation, the radiation emitted from various sources in our galaxy must be subtracted. He found that the total radiation emitted from our galaxy was greater than the sum total of emission from known sources, such as gas and dust. This *haze* may be due to the annihilation of dark matter particles and antiparticles. Rick Gaitskell, of Brown University, is looking in another direction; instead of looking outwards to the sky, he is conducting an experiment deep inside the Earth for evidence of dark matter. In an abandoned mine, an elaborate experiment has been constructed to detect energy emitted from a collision of a WIMP traveling to the Earth from outside our galaxy, with a xenon nucleus.

**Interactive Lab:** *Evolution of Large Scale Structure in the Universe.* Experiment with different initial conditions to see what structures form, and try to build a universe similar to the one we live in today.

**Activities:**

- The Hook: More Than We Can See (10 minutes)
- Activity 1: PhET "My Solar System" Simulation (30 minutes)
- Activity 2: Gravitational Lensing (20 minutes)
- Activity 3: Watch and Discuss the Video (50 minutes)
- Activity 4: How Do We Know that Dark Matter Exists? (20 minutes)
- Back to the Classroom (20 minutes)

**Nature of Science Themes:** *Evidence* and *Coherence & Consistency*. You may wish to display the *Evidence* and *Coherence & Consistency* icons during the session and remind participants of the central ideas of these themes. How do we know what we know? Measurements and observations are the raw materials from which we weave our stories, or explanations, about the world. Evidence consists of these data, processed through the logical framework of a model that support our hypotheses. Are the data consistent with the predictions of the model? If so, then the data can be used as evidence in support of the model. Science is not a set of independent facts and formulas (as often seen by students). Rather, scientific findings are accepted as true because they are coherent and consistent—they hold together with other ideas and findings. Conflicts between results or between experiment and theory reduce scientists' confidence in either the experiment or the theory.

**Evidence**
*How do we know?*

**Coherence & Consistency**
*How does it hook together?*

# Exploring the Unit

## *The Hook: More Than We Can See*

Time: 10 Minutes.

Purpose: To identify how dark matter relates to the other types of matter and energy in the universe.

Materials:

- Visualization of the Sloan Digital Sky Survey
- Example concept map from the online resource: *Facilitator's Guide High Resolution Graphics* (optional).

### *To Do and To Notice*

Show a dynamic visualization of the universe based on the Sloan Digital Sky Survey data (SDSS) indicating the structure of galaxies and clusters in the universe. For example, you might choose one or more of the following videos:

- "Mapping the Universe" (a visual "zoom out" from the earth based on SDSS data): http://video.google.com/videoplay?docid=-8252705102362324792&q=sdss# and at http://astro.uchicago.edu/cosmus/projects/sloanmovie/
- "A Walk Through the Universe" (a visual "fly through" of the universe based on SDSS data) http://www.vimeo.com/4169279
- "The Known Universe" (a visual "zoom out" from the Earth to see SDSS and CMB data and then back in to Earth) http://www.amnh.org/news/2009/12/the-known-Universe/ or at YouTube.

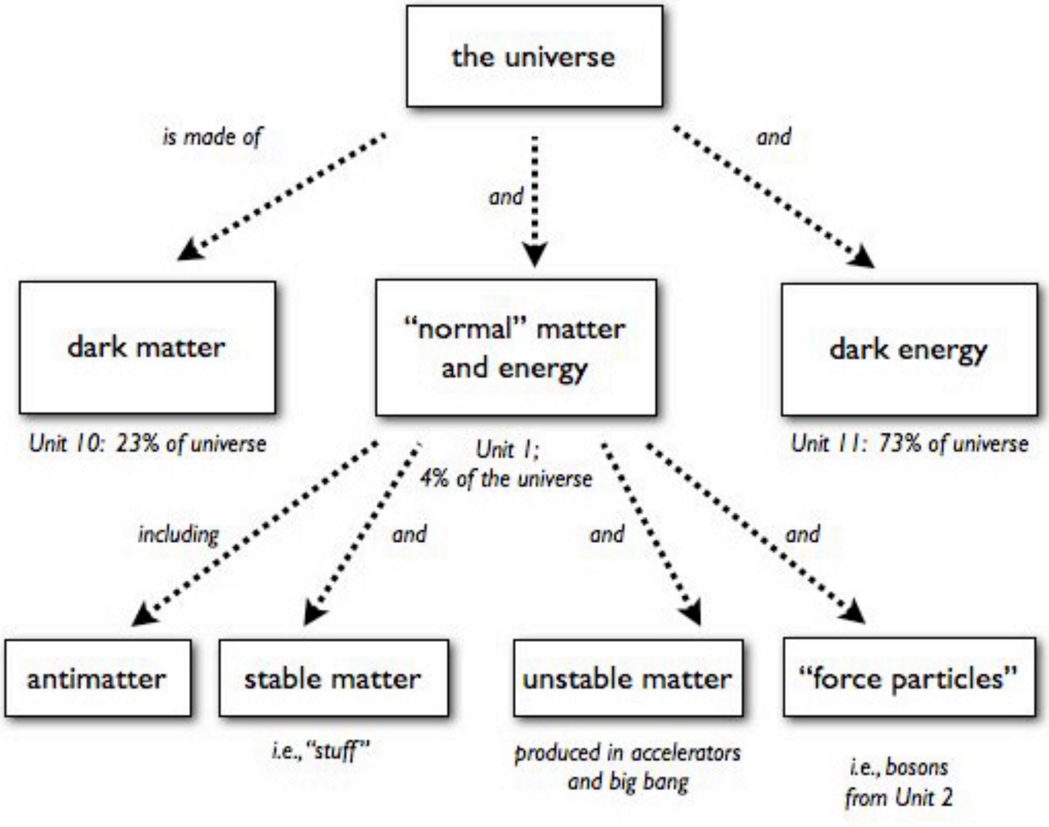
What are participants' reactions? What else is there in the universe than what we see here? How can you know that something is there if you can't see it? How can you know that something has mass if you can't see it? Emphasize ideas about nature of science, and explicitly elicit participants' ideas about dark matter. Discuss why dark matter is called "dark".

Ask participants to draw the next higher level (that which supercedes *matter* and *force* particles) on their concept map from Unit 1. What else exists other than the *particle universe* that formed the top level of our concept map in that unit? Where do dark matter and dark energy belong? After they have created their own, show them the example concept map on the next page and discuss all concept maps as a group.

### *What's Going On?*

The structure seen in the universe in the SDSS data could not have arisen just from what we see (the luminous matter). Dark matter is one of the things that we can't see in this data (as are dark energy and other forces). There are a variety of things that we know exist but can't see. For example, you can feel the effect of air molecules when you sit in front of a fan. But there are ways that we can measure the existence of these things by, for example, seeing how they affect things around them.

According to our current understanding, normal matter and energy comprises only 4% of the total matter and energy in the universe. Dark matter comprises 23%. Dark energy, which is the topic of the next unit, comprises another 73%.



**Example concept map**
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

## *Activity 1: PhET "My Solar System" Simulation*

Time: 30 Minutes.

Purpose: To explore the relationship between orbital velocity, radius, and the mass generating the gravitational attraction for orbital motion.

Materials:

- Tennis ball on string
- PhET "My Solar System" simulation at [http://phet.colorado.edu/simulations/sims.php?sim=My_Solar_System](http://phet.colorado.edu/simulations/sims.php?sim=My_Solar_System) (*Note:* Your computer does not need to be connected to the internet to run this simulation; select the "Download" option to download locally to your computer.)

### *To Do and To Notice*

Discuss the results of participants' experiments with the PhET "My Solar System" simulation from the homework while demonstrating on the digital projector.

1. **Demonstrate a circular orbit.** (*Note:* Use the following settings: mass body 1 = 200, mass body 2 = 1, x-position body 2 = 120, y-velocity body 2 = 130. Check "Show Grid" and "Tape Measure" and check that the orbit is circular using the gridlines and the tape measure.)

2. **Ask participants what they found when they reduced/increased the orbiting object's velocity.** Demonstrate that the orbit changes shape as velocity is gradually increased/decreased, and the orbiting object can crash into the sun (if the velocity is too low) or escape into space (if the velocity is too high). Discuss the relationship between a planet's velocity and its orbit. Note that the velocity in question is the *orbital* (or *angular) velocity* rather than *linear velocity* and briefly discuss the difference between the two.

3. **Ask participants how they kept the planet in orbit when the velocity was increased beyond the escape velocity.** (*Note:* It works to either increase mass 1, or mass 2. Emphasize increasing mass 1—mass 2 is very small in most systems.) Discuss the relationship between this experiment and dark matter—i.e., that the observation of high orbital velocities (for galaxies in clusters, or stars/gas in galaxies) did not match the observed mass at the center. Thus, the mass at the center must be larger than observed to keep the object in a *bound* orbit. This also means that, by observing an object's orbit, the mass responsible for that orbital motion (mass 1) can be deduced.

4. ***Optional:* Swing a ball on a string so that it traces a circle in the air**. Ask, "What do I need to do to make this ball move faster?" Discuss with participants how this is similar (and different) to the results with the PhET simulation. The muscle power required to make the ball's orbit speed up is analogous to the additional mass (and thus the extra pull of gravity) at the center of the solar system, making the planet's orbit speed up.

5. **Discuss participants' experimentation with orbital velocity and radius**. To keep an object in orbit when the orbital radius is decreased, the velocity must be increased to keep the planet from crashing into the sun. The sun has a stronger effect on the planet because of the reduced distance. To balance the increased gravitational potential energy for a smaller orbit, the kinetic energy must be increased.

6. **Use participants' planetary data from their homework to create a plot of velocity (y-axis) versus radius (x-axis).** You may wish to use a database (such as Excel) and its graphing tools. Below are the correct values with mass 1 = 200, mass 2 = 1.

| Radius | Speed |
|---|---|
| 30 | 260 |
| 50 | 200 |
| 90 | 150 |
| 115 | 132 |
| 120 | 129 |
| 140 | 120 |
| 150 | 116 |
| 167 | 110 |
| 175 | 108 |
| 200 | 100 |

You will obtain a curve where velocity drops with increasing radius.

7. **Show participants Vera Rubin's data for galactic rotation**, in the text. Why was this data surprising, given the results of the PhET experiment? How is this curve

Evidence

How do we know?

evidence for the existence of dark matter? How does this relate to *Evidence*? Is there another way to account for this data?

8. **Discuss results with participants.** Some possible points of discussion:

   a. **Galactic rotation**[1]. How do these results differ from the rotation of stars around a galaxy? The PhET simulation deals only with masses that are discrete—the mass of a galaxy is spread out in space. How do we use what we learned about gravity in Unit 3 to account for these two different situations?
   b. **How is dark matter distributed?**

### *What's Going On?*

An object of a given mass will stay in a circular or elliptical orbit only for a particular velocity—too fast, and it will fly off into space; too slow and it will crash into the object it is orbiting. If the velocity is faster than this optimal velocity, then the mass of the central object must increase in order to keep the orbiting object in orbit. This balances the increased kinetic energy with an increased gravitational attraction. Similarly, the closer that an orbiting object is to the central object, the larger the gravitational attraction, and the faster the orbital velocity. This is what was plotted in the graph of $v$ versus $r$. For those who are interested, velocity grows with $1/\sqrt{r}$: Assuming a circular orbit generated by a centripetal acceleration produced by gravity,

$$F = ma = \frac{GMm}{r^2} = m(\frac{v^2}{r})$$

$$\frac{v^2}{r} = \frac{GM}{r^2}$$

$$v = \sqrt{GM/r}$$

Vera Rubin's data didn't follow this curve—stars moved faster than they should have given their orbital radius. One way to explain this is that there is additional mass that the stars are rotating around. This is related to *Coherence & Consistency* because this conjecture is consistent with other laws of physics, such as the laws of gravity. The laws of gravity, instead, could be modified to account for these observations. Mention Modified Newtonian Dynamics (MOND), but this theory has not been as successful as dark matter in explaining a variety of observations.

**Coherence & Consistency**

***How does it hook together?***

This PhET simulation only shows discrete bodies orbiting other discrete bodies (like the Sun). In a galaxy, the matter of the galaxy is distributed through space, and not concentrated in one point. This is important because the matter inside an object's orbit exerts a gravitational pull on that object (the matter outside its orbit has no effect[2]). Stars further away from the center of the galaxy are further from the mass, but in turn are orbiting more mass (both dark and normal). This extra mass is just enough to counter the extra orbital distance, so the relationship between velocity and radius is essentially constant.

---

[1] *Galactic rotation* refers to the orbit of stars and gas around galaxies. *Galaxy cluster rotation* refers to the orbit of galaxies within clusters. Both exhibit velocities faster than expected, suggesting the presence of dark matter.

[2] This is Newton's Law of Universal Gravitation, or "Gauss' Law for Gravity."

How is dark matter distributed? Dark matter is densest at the center of a galaxy, becoming less dense further away. Galaxies are embedded in a *dark matter halo* that extends beyond the boundary of the galaxy. While there is some dark matter in the solar system, its effect is dwarfed by the sun's gravitational pull. Thus, the results from the PhET simulation are valid for the solar system. If all dark matter were similarly concentrated at the *center* of galaxies, instead of spread out through space, Vera Rubin's graph would have mimicked the one found in the PhET simulation.[3]

Take-home message: Astronomers infer the existence of dark matter by the fact that stars orbit galaxies faster than they should given the gravitational pull of the galaxy. This is similar to the results from the PhET simulation.

# *Activity 2: Gravitational Lensing*

Time: 20 Minutes.

Purpose: To demonstrate how gravitational lensing affects light reaching our telescopes.

Materials:

- One or several wine glasses with a curved bottom, as shown[4]
- Latex sheet model from Unit 3
- A heavy object (a stapler will do)
- A tennis ball
- Graph paper
- *Optional*: Images of light bending by a lens and light bending by gravity from online resources

Before the session: Experiment to find the best-sized dot to make on the graph paper for your particular wine glass.

## 1. Light bends by refraction

### *To Do and To Notice*

Make a large dot on the graph paper. Have participants put the wine glass over the graph paper and observe how it distorts both the grid of the graph paper, and the dot. If the dot is centered below the wine glass, they should view a ring. If it is not centered, they should see arcs. Experiment with and without liquid in the glass, with varying distances of source and lens, and by moving the lens from side to side. This can also be done as a demonstration for the class by using an overhead projector or illuminating the wine glass with a light source and projecting the image on the wall or floor.

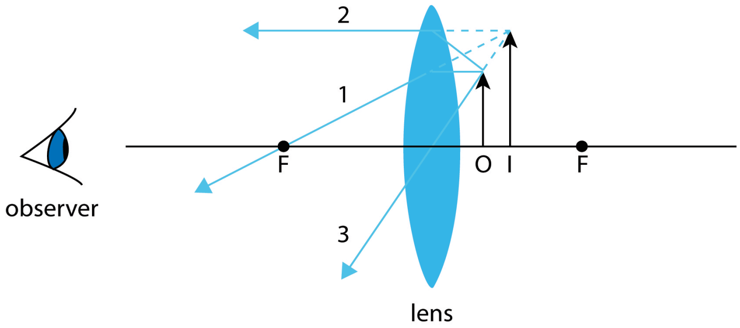
Remind participants that light is bent when it passes through materials, as when a pencil looks bent when it is in a cup of water. This is also how lenses work. Draw the following lens diagram on the board (or use the PhET simulation "Geometric Optics" http://phet.colorado.edu/en/simulation/geometric-optics). How would the image

---

[3] We don't recommend discussing initial *rise* in Vera Rubin's graph, which is arguably an artifact of the measurement techniques.

[4] Source: © Wikimedia Commons, License: None. Author: Will Murray, 23 December 2006. http://commons.wikimedia.org/wiki/File:Wine_Glass_%28Red%29.svg.

change if the object extended both above *and* below the center line? How would the image change if the object were a cross, centered on the center line?



**Light is bent by a lens, forming an image**
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

### *What's Going On?*

If the object extended above and below the center line, the image would also extend above and below the center line. If the object were a cross, the image would also be a cross. Thus, an object that extends in all directions in the x-y plane (such as a dot on a piece of paper) would create an image that is a disk. Since the center of the wine glass is very thick, the dot on the paper turns into a ring.

## 2. Light is bent by gravity

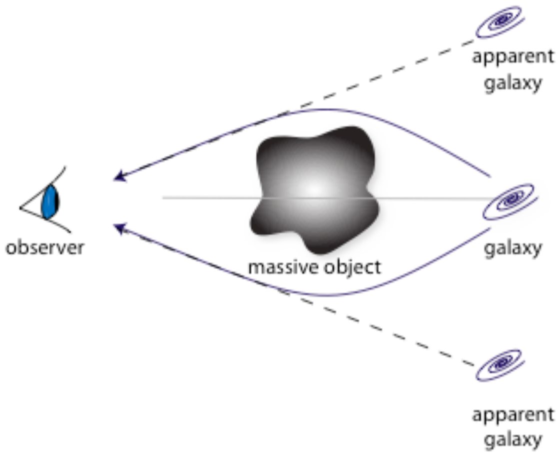
### *To Do and To Notice*

Remind participants of what they learned in Unit 3—we know that light is bent by gravity—but only a little bit, or else flashlight beams would curve dramatically towards Earth. Have four participants hold the latex sheet at the corners, with the heavy object in the middle. Roll the tennis ball across the sheet, and ask participants what they notice. The ball curves towards the heavy object just as light curves when traveling around a heavy mass. However, since light is moving much faster than the tennis ball, it only curves when traveling by very massive things.

Draw the following diagram on the board, without the apparent galaxies. Explain that this is how light is bent by a galaxy. Ask participants, "Where does it appear that the galaxy is located?" Based on their responses, draw the dotted lines showing the location of the apparent galaxies. As with the wine glass experiment, help participants visualize that if the diagram is extended in all dimensions, the two apparent galaxies turn into an apparent galaxy ring, called an *Einstein ring.*[5] Brainstorm: How is a gravitational lens different from an optical lens?

---

[5] For participants who are curious, the wine glass demonstration is a good approximation of gravitational lensing because light passing near a massive object is deflected by an angle that is related to $1/r$, where r is the distance from the center of the object to the nearest point where the light passes it by. A wine glass is thicker at the center and thinner at the edge, and its thickness is approximately related to $1/r$, where r is the distance from the center. Thus, the wine glass deflects light in a similar fashion to a massive object.



**Light is bent by a massive object, forming apparent galaxy images**
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

### *What's Going On?*

So even though we can't see dark matter, we can detect it through its effects on light traveling to us from distant galaxies and clusters. When we see a warped image, we can infer something about the lens that has warped it.

A gravitational lens is different from an optical lens in several ways:

- Both bend light, but bend it in different ways (the resulting image is different)
- The effective curvatures of the two lenses are different
- In a gravitational lens, a ring (rather than a disk) is the image resulting from a point of light
- A lens bends light at the interface only; a gravitational lens bends it continuously
- A gravitational lens shows us an apparent image that is similar to a virtual image in a lens—we perceive the location of the image based on light rays that appear to be emanating from that point

### *Going Further*

Show participants images from Hubble resulting from gravitational lenses in space. How do these images relate to the theme of Evidence?

**Evidence**
*How do we know?*

- http://hubblesite.org/newscenter/archive/releases/1996/10/image/a/. Note that all the images of the blue galaxy look somewhat similar. These are the same galaxy, much as shown in the drawing, above. Note that this page has a good explanation of how the images from Hubble are analogous to the wine glass experiment.

- For those who want more, see the following links. Which of these images show an object that is directly on the other side of the gravitational lens? Which show an object that is well off-center of the lens?
  - http://hubblesite.org/newscenter/archive/releases/exotic/gravitational-lens/2004/08/results/100/
  - http://hubblesite.org/gallery/album/exotic/gravitational_lens/pr2003001e/titles/true/
  - http://hubblesite.org/newscenter/archive/releases/2009/25/image/ao/

Show participants the image of the Bullet Cluster from the text or at http://hubblesite.org/newscenter/archive/releases/exotic/dark%20matter/2006/39/image/a/. This is an image of a collision of two galaxy clusters. From standard observational techniques, astronomers measured the normal (luminous) gas from the two clusters, shown in pink.

Ask participants, what would you expect to happen if two groups of people were walking towards each other on a narrow street and the two groups collide?

> Answer: Two groups of people would slow and stop, just like the two galaxy clusters (shown in pink) have run into one another and slowed[6].

Ask participants to imagine that each group of people was accompanied by a group of butterflies, flying at the same speed as the people are walking. What happens to the butterflies when the people bump into each other?

> Answer: The groups of butterflies will continue to fly forward, not bumping into one another, and thus not slow. Using gravitational lensing, astronomers were able to deduce the total matter present in the two clusters. The total matter (shown in blue) has passed through the collision without interacting, like the butterflies in the analogy. This dark matter has bypassed the point of collision, as expected for a weakly interacting form of matter. This is considered key evidence for dark matter. Ask participants if there are other analogies that they can imagine for what they see in this image.

## *Activity 3: Watch and Discuss the Video*

VIDEO

Time: 50 Minutes.

If participants are watching the video in class, have them view it now. Remind them of the guiding questions listed in *Between Session*s from the previous unit.

Discuss the video with participants, focusing on the evidence for dark matter from each experiment.

Key evidence for dark matter in each experiment:

- Finkbeiner: He found extra emission in WMAP, called the WMAP haze, possibly created by dark matter annihilation.
- Gaitskell: If he sees light emission, then the amount and position of that light will be a clue to the presence of dark matter, created in collisions between dark matter and normal matter. (*Note:* The interaction between dark matter particles from space and a nucleus here on earth can be modeled by rolling 10 tennis balls towards a single golf ball—only rarely will a tennis ball hit a golf ball).

---

[6] Note: Galaxy collisions don't generally involve actual *collisions*. Rather, the two galaxies interact gravitationally, and slow down.

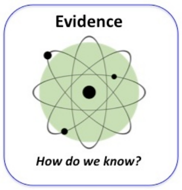
# *Activity 4: How Do We Know Dark Matter Exists?*

Time: 20 Minutes.

Purpose: To discuss how the multiple pieces of data provide a consistent and coherent set of evidence for the existence of dark matter.

### *To Do and To Notice*

Discuss the following questions as a group:



1. How do we know that dark matter exists? As a group, create a list of the evidence and discuss in light of the theme of *Evidence*.
2. What would Finkbeiner and Gaitskell's experiments add to this evidence?
3. What do we know about the nature of dark matter?
4. What evidence would you want to see that would prove to you that dark matter exists?

### *What's Going On?*

**1. How do we know that dark matter exists?**

- **Galaxy rotation** (Rubin). The speed of stars orbiting in galaxies is too large—they must be embedded in dark matter.
- **Galaxy cluster rotation** (Zwicky). The speed of galaxies orbiting in clusters is too large—they must be embedded in dark matter.
- **Gravitational lensing.** The distortion of light tells us that there are objects we can't see.
- **Cosmic microwave background** (CMB). The CMB is an image of how "lumpy" the regular matter in the universe was shortly after the Big Bang. These concentrations of matter acted as gravity sinks, drawing more matter to them. However, the lumps we see in the CMB are too small to have had enough gravitational force and attract the matter to see the galaxies and structure we see today (from the Sloan Digital Sky Survey, see *Hook*). If this normal matter were accompanied by dark matter, however, these early lumps would have had enough gravitational attraction to create the universe we see today. If you've ever made rock candy, you know that the sugar needs something to cling to (the string) in order to grow into crystals. In the case of the universe, the "seeds" for structure is the lumps in the CMB.
- **Galactic simulations** (Ostriker and Peebles). The observed structure of galaxies only emerges if a uniformly distributed invisible mass was present as they evolved.
- **Particle physics** ("Big Bang nucleosynthesis"). From the ratio of different elements in the universe, cosmologists can determine the abundance of normal matter in the universe (4%). Since other measurements tell us that dark matter is 23% of the mass-energy of the universe, it must be some new, exotic form of matter (not just normal matter that's not glowing).

**2. What would Finkbeiner and Gaitskell's experiments add to this evidence?** These observations are more direct and less inferential, and the logical or causal chain is (perhaps) shorter than in other observations. Their experiments, if positive, give additional evidence for the existence of dark matter. These experiments would also give us new information about the nature of dark matter.

**3. What do we know about the nature of dark matter?** Brainstorm as a group. Below are some possible answers.

- Dark matter is the primary source of gravity in the universe.
- Dark matter is by far the most abundant form of matter in the universe.
- A variety of pieces of evidence suggest that dark matter exists.
- Dark matter does not emit, block, or scatter light.
- Dark matter is an exotic form of matter (not just normal matter that doesn't emit light).
- Our models suggest that dark matter is probably one of three things—axions, WIMPs, or MACHOs.

**4. What evidence would you want to see that would *prove* to you that dark matter exists?** Brainstorm as a group. Some participants may feel that the existence is already proven. Some may argue that nothing can ever be proven beyond a doubt. Discuss the nature of evidence and proof in science.

# Back to the Classroom

Time: 20 Minutes.

Following is a list of high school topics and standards that are relevant to this material. See http://strandmaps.nsdl.org/ for a visual representation of science standards and benchmarks. Facilitate a discussion with participants:

- **Where might this unit fit into your curriculum?** Brainstorm a list of topics with participants. You may share additional items from the list below, as you see fit.
- **What do your students know about this topic?** Brainstorm with participants.
- Optionally, you may ask participants to **find one or more of the relevant topics on the Science Literacy Maps**, and explore related ideas and misconceptions.

## Topics and Standards

**Forces and Motion**. Gravitational force is an attraction between two masses; the strength of the force is proportional to the masses and weakens rapidly with distance between them. Gravity is the force that keeps planets in orbit around the sun. If a force acts towards a single center, the object's path may curve into an orbit around the center. The change in motion (direction of speed) of an object is proportional to the applied force and inversely proportional to the mass.

**Energy.** The total amount of energy remains constant if no energy is transferred into or out of a system. In order for the total energy to remain constant (and equal to zero) when a planet (or other orbiting object) moves closer to the mass generating the gravitational pull, the kinetic energy of the planet must balance the increased gravitational potential energy; thus, the planet's velocity must increase.

**Size and Scale.** When describing and comparing very small and very large quantities, express them using powers-of-ten notation. Natural phenomena often involve sizes, durations, and speeds that are extremely small or extremely large. These phenomena may be difficult to appreciate because they involve magnitudes outside our experience.

**Waves and Light.** For an object to be seen, light must be emitted by or scattered from it. Visible light is a small band in the electromagnetic spectrum.

**The Universe.** The universe is estimated to be over 10 billion years old and to have originated in the Big Bang. Some distant galaxies are so far away that their light takes several billion years to reach the Earth—therefore, they are seen as they were that long ago in the past.

**The Solar System.** Gravity is the force that keeps planets in orbit around the sun.

**Nature of Science.** The selection of appropriate measurement and observation tools is important in answering a particular experimental question. For some of these observations, increasingly sophisticated technology is used to learn about the universe. Mathematical models and computer simulations are used in studying evidence from many sources in order to form a scientific account of the universe. Scientists formulate and test their explanations of nature using observation, experiments, and theoretical and mathematical models. Although all scientific ideas are tentative and subject to change and improvement, for most major ideas in science there is much experimental and observational confirmation. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations. Observation, evidence, and logic are important in the interpretation of experimental results.

## Classroom Resources

**PhET interactive simulations**, and accompanying teacher-created activities, at http://phet.colorado.edu.

**NASA's *Imagine the Universe* teachers' site** with lesson plans and more:
http://imagine.gsfc.nasa.gov/docs/teachers/teachers_corner.html. See the "resources" section for a list of topics on dark matter:
http://imagine.gsfc.nasa.gov/docs/resources/resources_a.html#dark_matter.

**The Mystery of Dark Matter** teacher's guide and games from the Perimeter Institute. Excellent and very detailed lesson plans, hands-on activities, sample calculations, conceptual questions, and curriculum links. Don't miss the simple but fun dark matter video game.
http://www.perimeterinstitute.ca/Perimeter_Explorations/The_Mystery_of_Dark_Matter/The_Mystery_of_Dark_Matter/.

**Astronomy activities, including dark matter**, from NASA and Sonoma State University: http://universe.sonoma.edu/activities/.

**Galactic rotation activity** from the University of California at Irvine Observatory Astronomy Outreach Program:
http://www.physics.uci.edu/~observat/astro_activities_teachers.html.

**Universe Adventure** online interactive textbook about cosmology from University of California at Berkeley, with teacher activities on the Big Bang and Cosmic Background Radiation: http://universeadventure.org/index/teachers.htm.

**Cosmic Times.** A collection of curriculum materials for grades 7-12 that traces the history of our understanding of the universe from general relativity to the discovery of dark energy in newspaper-style posters including inquiry lessons. http://cosmictimes.gsfc.nasa.gov/.

**NOVA's scienceNOW feature on Dark Matter**, with teacher's guide and lesson plans: http://www.pbs.org/wgbh/nova/teachers/viewing/0301_01_nsn.html.

**Galaxies and Dark Matter—1 hr video lesson**, including demonstrations, lecture, and discussion questions. http://blossoms.mit.edu/video/fisher/fisher-watch.html.

**Gravitational Lenses.** Three teaching activities on gravitational lenses:

1. R. M. Ros (2008), Gravitational lenses in the classroom, *Phys. Educ.* **43**(5), 506-514
2. M. Falbo-Kenkel and J. Lohre (1996), Simple gravitational lens demonstrations, *Phys. Teach.* **34**(9), 555-558.
3. Exploratorium, http://www.exo.net/~pauld/activities/astronomy/gravitationallens.htm.

***Your Cosmic Context: An Introduction to Modern Cosmology***, Todd Duncan and Craig Tyler, Pearson: Addison-Wesley, 2009. A very readable and lively text including many topics found in this course, such as general relativity, the expansion of the universe, redshift, the cosmic microwave background, dark matter, and dark energy. Highly recommended.

# Between Sessions

## FACILITATOR

You may wish to share the *Classroom Resources* section of the next unit with participants for their homework.

You may wish to share the learning goals of the next unit from *What Will Participants Learn?* with participants in preparation for the next session.

## PARTICIPANTS

**Text:** Read Unit 11: *Dark Energy.* While you read, think about how astronomers measure and observe the universe. Make a list of the following items that you notice as you read:

1. Measurement tools used by astronomers (e.g., telescopes)
2. The measurements that each tool allows astronomers to make (e.g., the shape and position of objects in the sky).

**Video:** While watching the video for Unit 11, focus on the following questions:

1. How do we know that dark energy exists? In particular, what are the logical chains suggesting, in each experiment, that dark energy exists?
2. What are the researchers' premises?
3. What did they observe?
4. What did they conclude?

**Interactive Lab:** You may wish to explore the Interactive Lab associated with this unit: *Evolution of Large Scale Structure in the Universe.* Experiment with different initial conditions to see what structures form, and try to build a universe similar to the one we live in today.