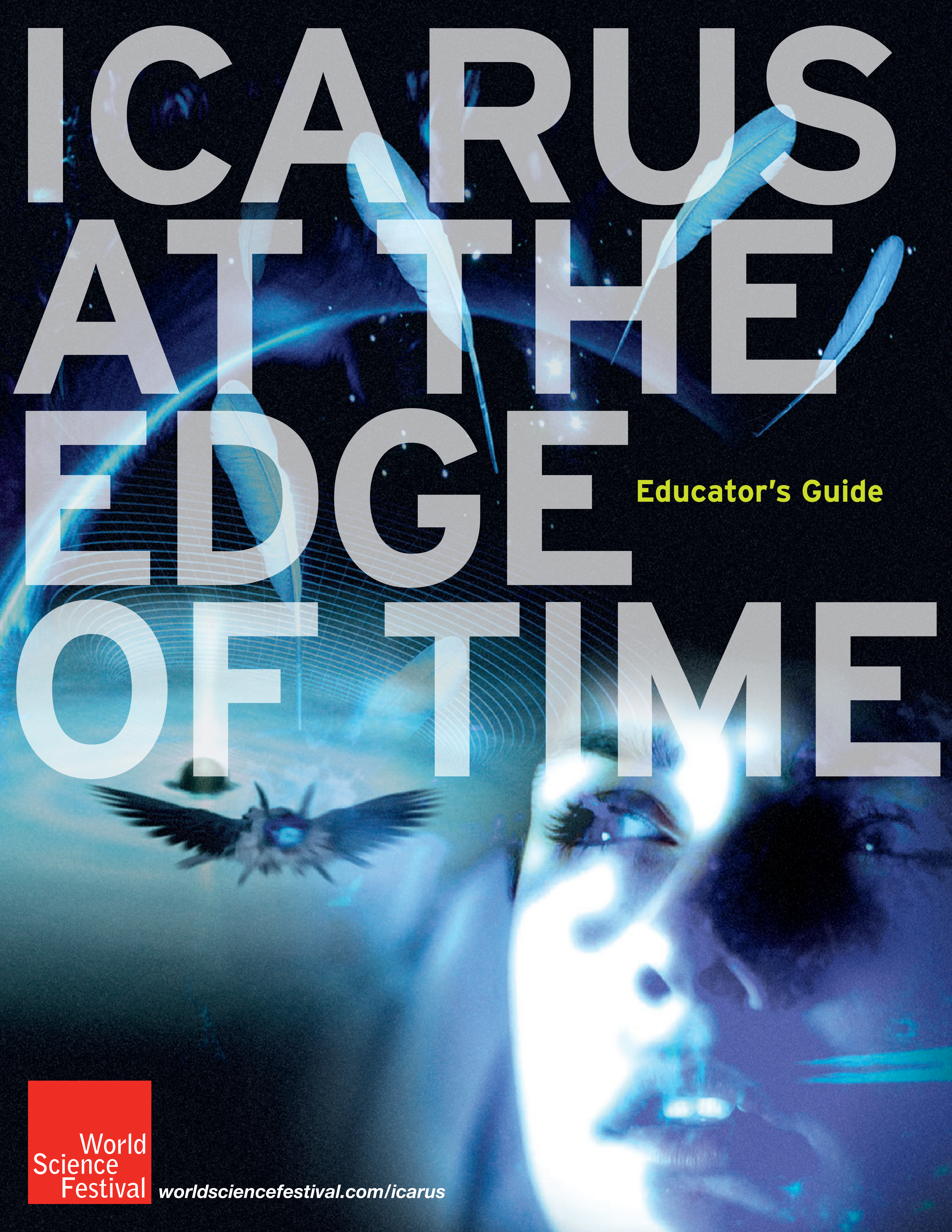
ICARUS AT THE EDGE OF TIME

Educator's Guide



World Science Festival

worldsciencefestival.com/icarus

Have you ever dreamed of setting out on a heart-thumping adventure?

Greek mythology tells the story of Icarus, a boy who defied his father, flew too close to the sun on wings of wax, and plummeted to the sea when the wings melted. *Icarus at the Edge of Time* is about a different boy, one who dares to fly close to a black hole and lives to tell the tale.

The Greek myth suggests that it's too dangerous to try something new. But doing what has never been done before, even if there are risks, is exactly what scientists need to do to make great breakthroughs.

Physicist Brian Greene rethought the Icarus myth to inspire people and encourage scientific exploration. He began by writing *Icarus at the Edge of Time* as a children's book and then transformed the story into a multimedia show. "My intention was to make a performance piece that would have the same wonderful drama, music, and edge-of-the-seat quality as some of the greatest works," Greene explains, "but where the narrative would be driven by science."

HOW TO USE THIS GUIDE

Use the background material and activities in this guide to integrate *Icarus at the Edge of Time* into your classroom curriculum.

PLAN YOUR VISIT

To find information on directions and reservations, or to download a PDF of this guide, visit: **worldsciencefestival.com/icarus**

BEFORE THE SHOW

Review *The Science Behind the Story* and *Correlation to Standards* to see how the show connects to your curriculum. Pre-show activities focus on basic physics related to black holes, such as density, gravity, and the lifecycle of a star.

AFTER THE SHOW

Review the main content points from the show with your class. Post-show activities focus on the effects of a black hole on time, and encourage creative expression of what it would be like to visit one.

THE STORY

When the story begins, Icarus is on the powerful spaceship *Proxima*, headed toward an earth-like planet orbiting Proxima Centauri, the star closest to the Sun. A 25-trillion-mile journey that will take over a century, it began with Icarus' great-grandfather leading the mission and will end when Icarus' own children arrive.

Icarus yearns to be something more than just a link in a chain. When the ship nears an uncharted black hole, he jumps at the chance to explore it. His father refuses to let him go, saying that it's too dangerous, but Icarus slips away. He flies close to the black hole, circling it at a safe distance, delighted both by the marvelous sight and by his own daring. After an hour, Icarus heads back to the *Proxima* to share his triumph with his father.

But the *Proxima* is gone. Instead Icarus sees an interstellar highway busy with hundreds of starships. He docks aboard one, discovers that thousands of years have passed, and realizes that he had forgotten about the effect of gravity on time. He has achieved his goal at the terrible cost of losing everyone that he cared about.

In the ship's library, he learns about the original *Proxima*'s journey, the creation of a galactic government, new discoveries. And about the legend of a boy, who, despite his father's warning, flew close to a black hole and never came back. Except that he did.

How can a “short trip” to the edge of a black hole have such a huge impact on Icarus, effectively sending him thousands of years into the future? To understand what black holes are, and how they warp space and time, it all begins with gravity.

THE SCIENCE BEHIND THE STORY

What is Gravity?

BEFORE THE 17TH CENTURY, gravity was a mysterious force to most people. They knew that an apple falling from a tree would always fall to the ground. They also knew that the Moon would stay in its orbit without falling to Earth. But they didn’t understand that the same physical force—gravity—affects both the apple and the Moon.

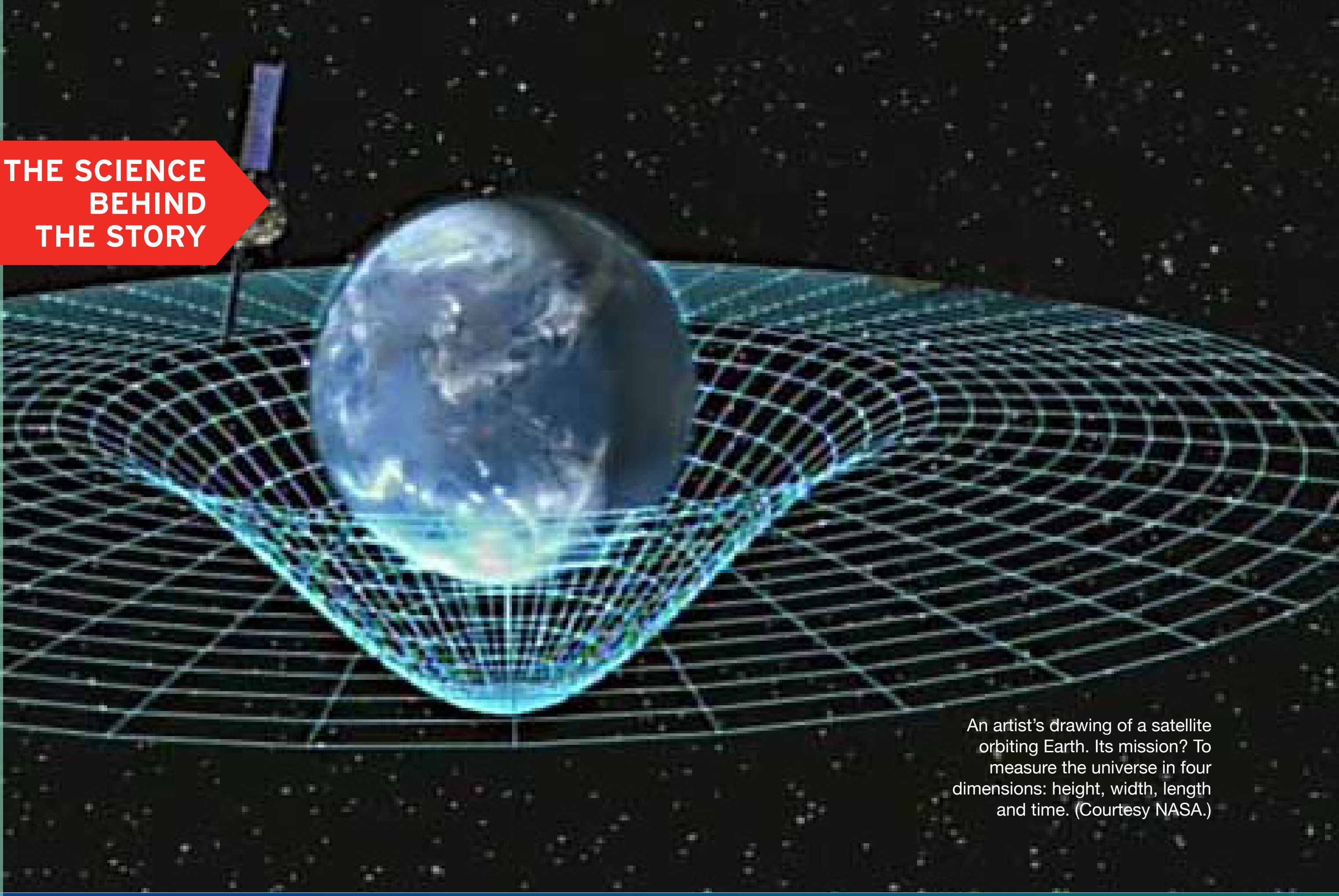
Then along came the English scientist Isaac Newton, who united the heavens and Earth. He explained that gravity is the force of attraction between *any* two objects, and the strength of the attraction depends on the mass of the objects and the distance between them.

Newton believed that gravity is the glue of everyday life, affecting objects on Earth and in space alike, and he came up with a mathematical equation to predict everything from how baseballs fly through the air to the paths of planetary orbits.

Underlying this theory was Newton’s view of space. It might look like nothing, but space was actually something—an immense, unchanging stage on which objects existed and action happened, including gravitational attraction.


An artist’s rendering of the Milky Way. Stars stud its spiraling arms. (Courtesy NASA/JPL-Caltech.)

THE SCIENCE BEHIND THE STORY



An artist's drawing of a satellite orbiting Earth. Its mission? To measure the universe in four dimensions: height, width, length and time. (Courtesy NASA.)

How Does Gravity Work Across Space?

Newton's theory lets us make accurate predictions about the strength of gravitational attraction, but it doesn't explain how gravity actually works. For example, how does the Sun reach across 93 million miles of seemingly empty space to affect Earth? Newton was well aware of this problem, but left it to the work of future thinkers.

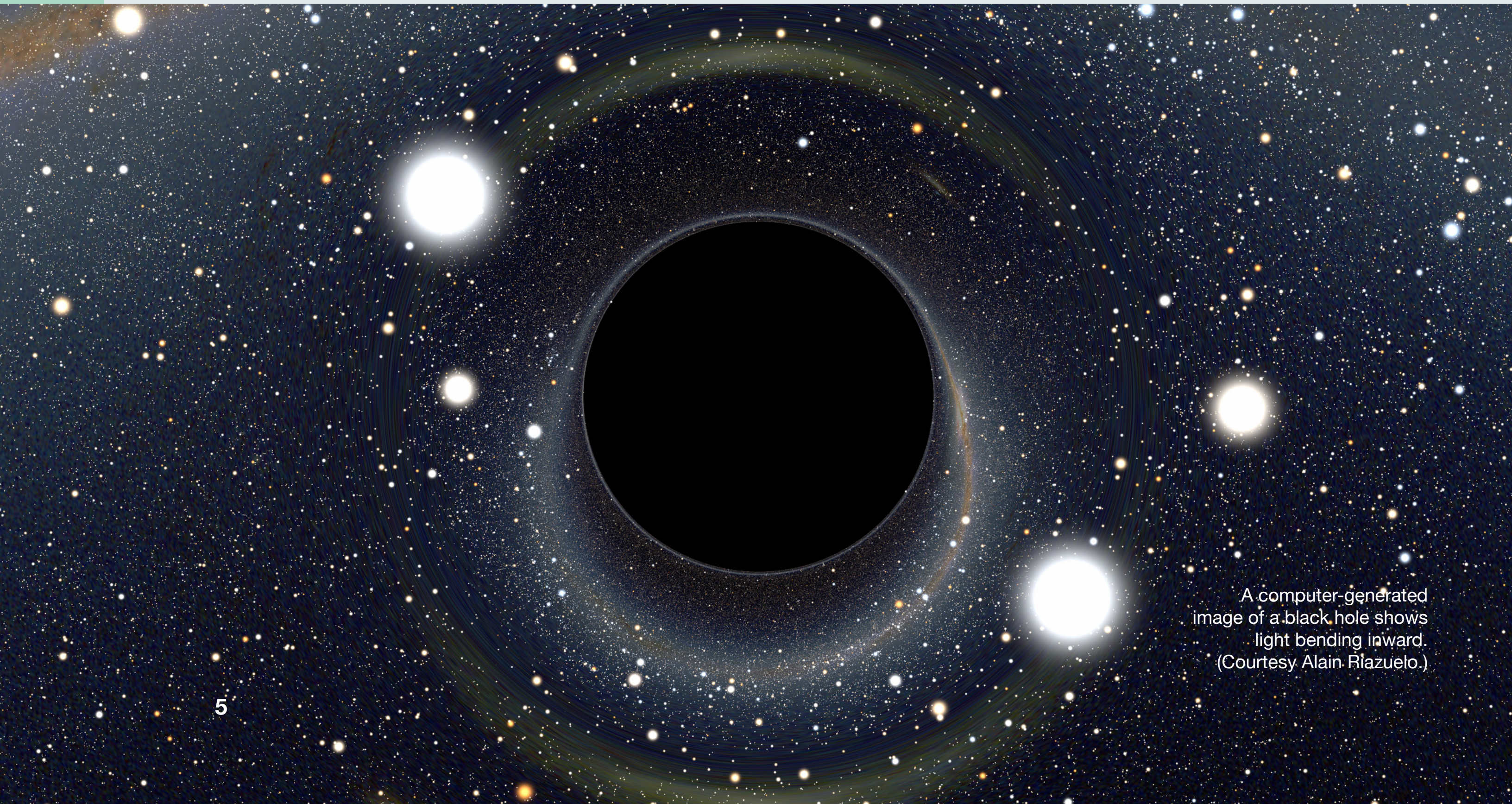
In the early 20th century, Albert Einstein took up the challenge, beginning with the question of how we think about space. For Newton, space was a passive background, unaffected by the objects within it. But Einstein suggested instead that space was active and dynamic, that it could bend and twist and ripple. Without any objects in it, space would be flat. The presence of an object, however, would cause space to warp around the object, like the indentation created by putting a bowling ball on top of stretched fabric. This warp of space communicates the force of gravity, affecting other objects. What this means is that Earth creates a gravitational well in space, and the less massive Moon is kept in orbit because it rolls along the edge of that well—and Earth rolls along a similar but much larger gravitational well created by the more massive Sun. So what makes gravity work through space is actually the warping of space itself.

THE SCIENCE BEHIND THE STORY

What is a Black Hole?

Einstein published his explanation of gravity in 1916, at the height of World War I. That same year, German astronomer Karl Schwarzschild was fighting on the Russian front, where he was in charge of calculating artillery trajectories—that is, thinking about how small, heavy cannonballs travel through space. When he came across Einstein's theory, he got excited. He soon realized that if an object were sufficiently small and **dense**, such as a compressed **star**, it would warp space so severely that objects that came too close would be unable to escape its gravitational grip. It would be like a whirlpool or a waterfall pulling everything into it. Not even light would be able to escape, so Schwarzchild called this phenomenon a "dark" or "frozen" star. Later, physicist John Wheeler gave it a catchier name, a "**black hole**"—black because it would emit no light, a hole because anything too close would fall into it. Only objects that stay beyond the **event horizon**, the boundary where the gravitational pull becomes irresistible, would be able to escape.

Schwarzschild sent his theory to Einstein, who thought the idea was interesting and mathematically valid. But not everything that is true mathematically is true physically, and Einstein was skeptical that black holes existed in reality. What evidence was there? And how could something become that small and dense? For our own Sun to form a black hole, it would need to be crushed to only a couple of miles across, at which point a teaspoonful of it would weigh as much as Mount Everest. How could such a thing happen?



A computer-generated image of a black hole shows light bending inward. (Courtesy Alain Riazuelo.)

THE SCIENCE BEHIND THE STORY

A snapshot of fiery star birth. (NASA/JPL-Caltech/ Harvard-Smithsonian.)

Do Black Holes Actually Exist?

There is growing evidence that black holes are real, from two main sources. First, by studying the lifecycle of stars, scientists now understand how a black hole could form. When a star is born, its **core** ignites, starting a process of **nuclear fusion** that can last for billions of years. Fusion produces streaming radiation that pushes out toward the surface of the star, which balances the inward pull of gravity and prevents the star from collapsing under its own weight. But this **hydrostatic equilibrium** is altered when the star eventually burns through the fuel in its core and the outward push can no longer balance the inward pull of gravity.

When the core of a super massive star collapses, it releases so much energy that it blasts itself apart. What survives depends on the mass of the tiny, dense core. If it is less than about three times the mass of the Sun, it will shrink into a dense neutron star. But if it has a greater mass, it collapses into a black hole.

The second type of evidence comes from observations. Since black holes emit no light, we can't see them directly. But we can see their effect on objects around them. For example, as dust and gas from stars fall toward a nearby black hole, they accelerate to nearly the speed of light and heat up, giving off visible light and X-rays. This light is produced beyond the event horizon, so it can escape and we can see it. Astronomers have also seen stars whipping around a central object, which they conclude must be a black hole, because no other object would exert enough gravitational pull.

Unlike what Einstein thought, evidence suggests not only that black holes exist, but that they are plentiful.

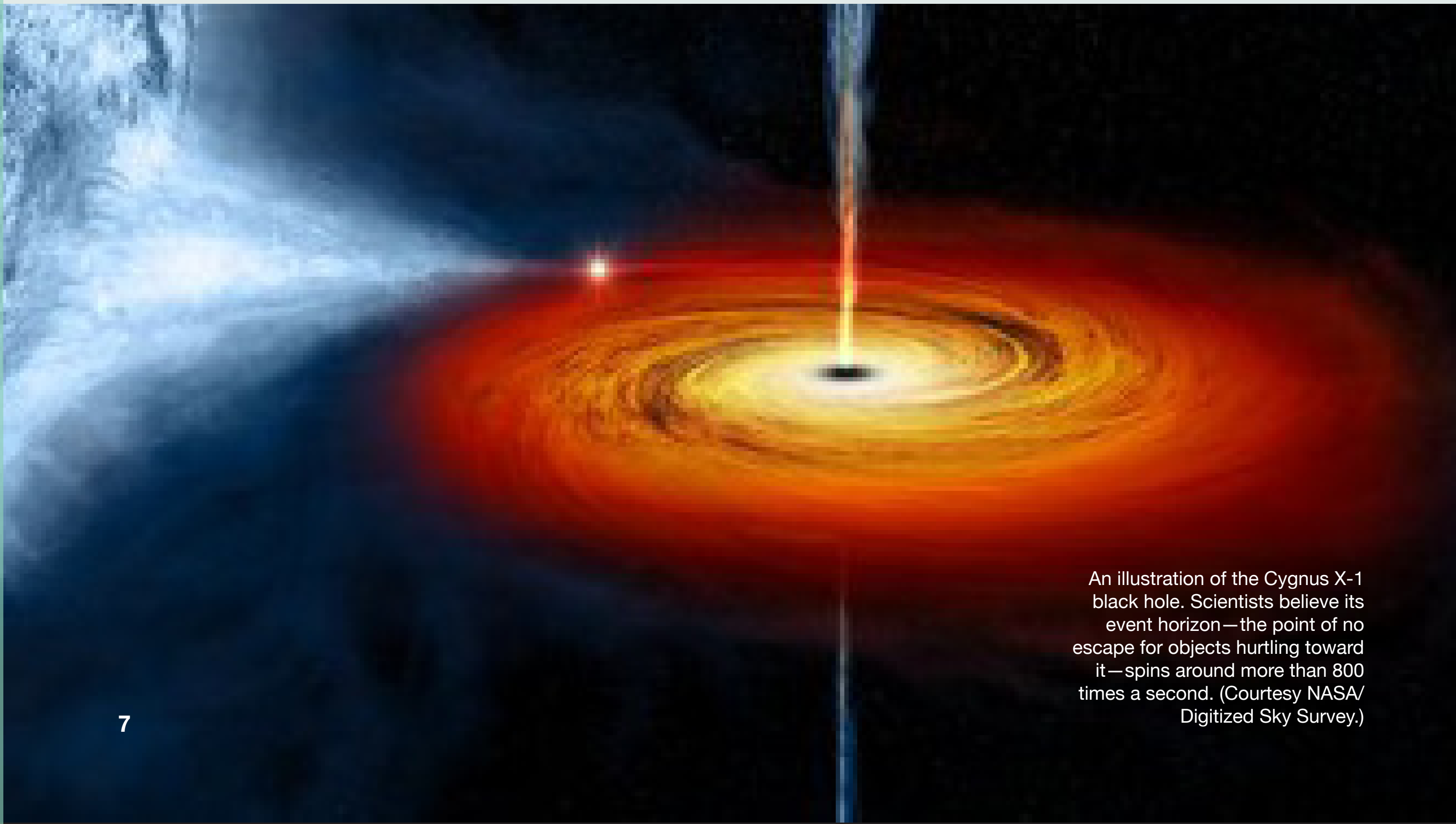
THE SCIENCE BEHIND THE STORY

What Time is It?

The more we learn about black holes, the more amazing they seem. We now know that black holes not only warp space dramatically, but also warp time.

Einstein believed that space and time are really a combined unit he thought of as space-time, so the gravitational pull caused by a massive object would distort both space and time. The closer you are to the object, the more slowly time passes; the further away, the faster time passes. This is called **time dilation**. Physicists at the National Institute of Standards and Technology in Colorado have been able to measure this effect. Using two of the world's most precise clocks, they discovered that a clock placed one foot higher than another clock ticked a little bit faster, because it was slightly less affected by Earth's gravitational pull. This means that if you lived at the top of the Empire State Building, you would age faster than someone on the ground. But the difference would be only 104 millionths of a second over the course of an entire lifetime.

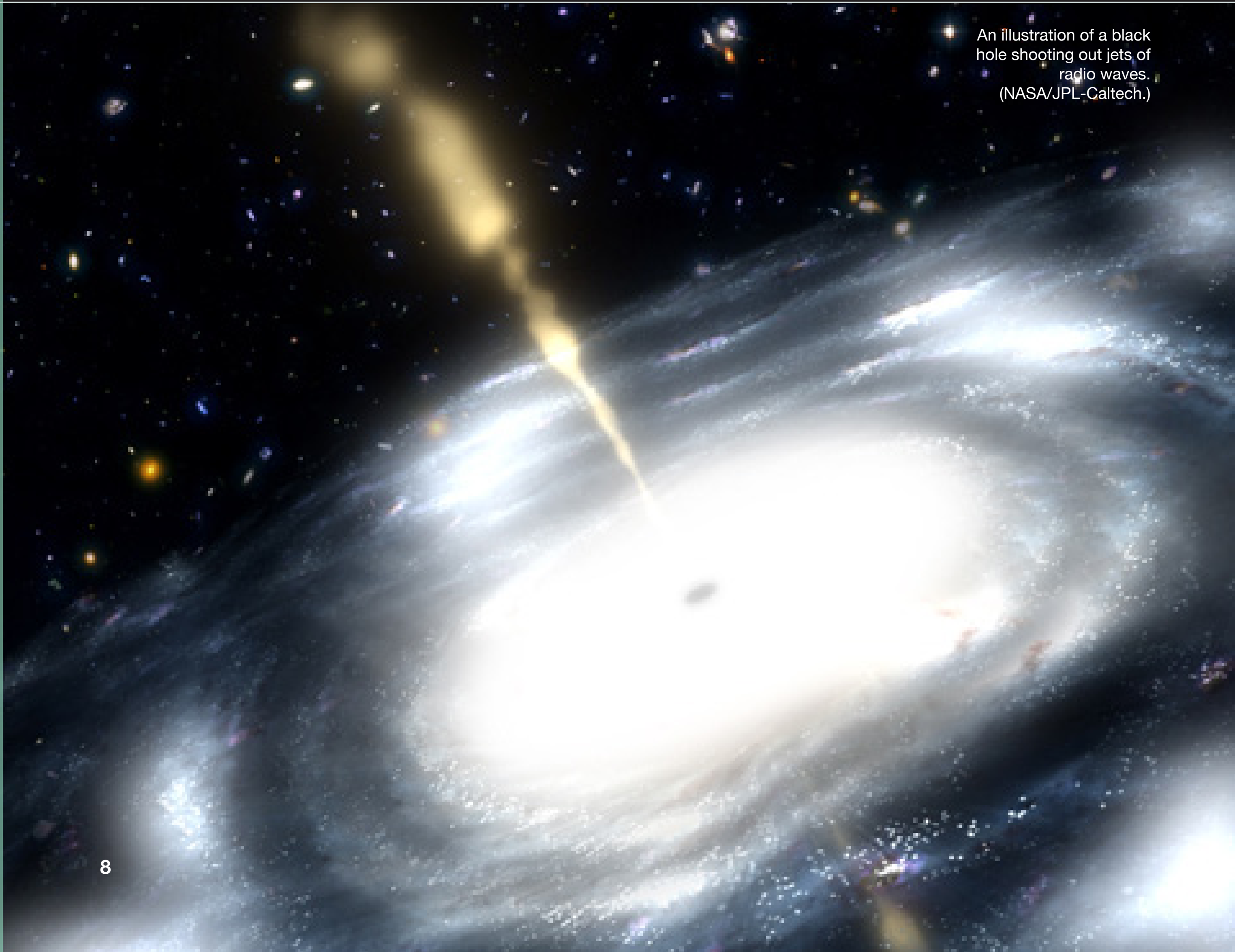
In contrast, the time dilation that could occur near a black hole is immense, because the gravitational pull is so strong. The closer you came to a black hole, the more time would slow down relative to the passage of time for someone far away. Depending on the size of the black hole, how close you were to it, and how long you stayed there, what might seem like a short time for you could be hundreds or even thousands of years for someone on Earth!



An illustration of the Cygnus X-1 black hole. Scientists believe its event horizon—the point of no escape for objects hurtling toward it—spins around more than 800 times a second. (Courtesy NASA/ Digitized Sky Survey.)

Much More to Discover...

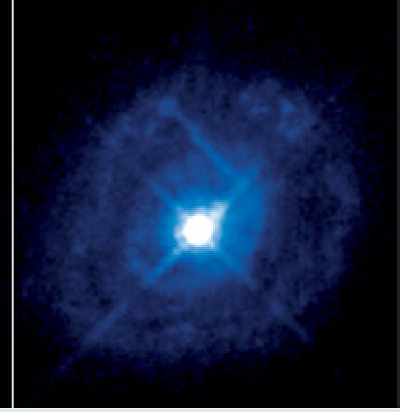
Our understanding of black holes has come a long way in the last century, but there's still a lot we don't know. One big one is what's at the center of a black hole. Some scientists think that a black hole's core is where time comes to an end, or is possibly even a portal to another universe. Finding the answer to mysteries like these is one of the great remaining challenges we face.



An illustration of a black hole shooting out jets of radio waves. (NASA/JPL-Caltech.)

GLOSSARY

BLACK HOLE: A region of space whose gravitational pull is so strong that anything that gets too close, even light, cannot escape.



CORE: The center of a star, where nuclear fusion occurs.

DENSITY: How much mass exists within a given volume.

EVENT HORIZON: The boundary surrounding a black hole beyond which nothing can escape the black hole's gravitational pull.

GRAVITY: The force of attraction between objects. The strength of attraction is determined by the mass of the objects and the distance between them.

HYDROSTATIC EQUILIBRIUM: In a star, the balance between streaming radiation (produced by nuclear fusion) that pushes out toward the surface of the star and the inward pull of the star's own gravity.

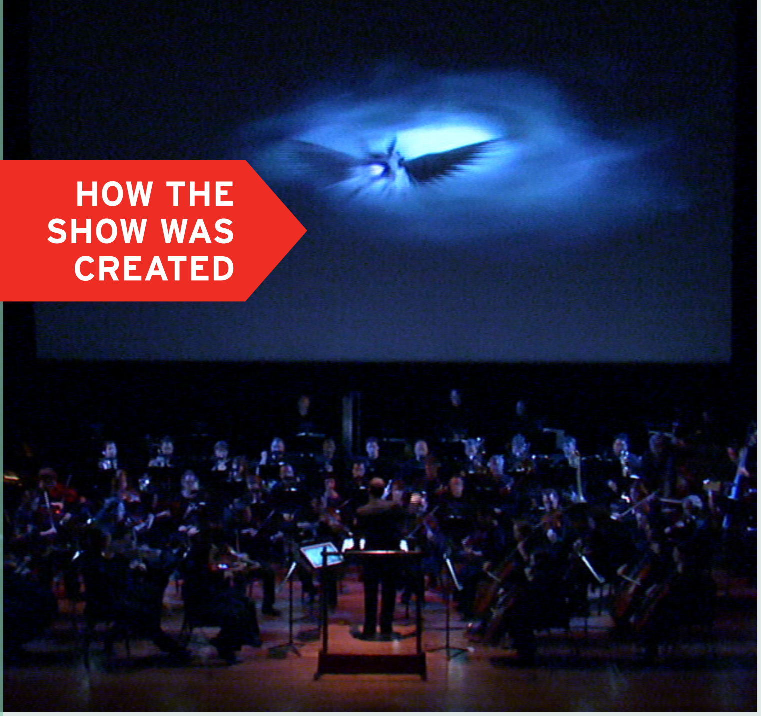
MASS: How much matter an object contains.

NUCLEAR FUSION: The process at work in the core of a star, in which atoms combine at high temperature and pressure, releasing intense energy and light.

STAR: A huge ball of hot gas with nuclear fusion at its core.

SUPERNOVA: An explosion that happens when a high mass star can no longer maintain hydrostatic equilibrium and its core collapses in on itself.

TIME DILATION: The warping of time due to the influence of gravity. The stronger the gravitational pull, the slower time passes.



HOW THE SHOW WAS CREATED

PHYSICIST BRIAN GREENE worked with playwright David Henry Hwang to adapt *Icarus at the Edge of Time* for live narration, and invited renowned composer Philip Glass to write the music that would bring the story to life. To round out the experience, making it as immersive as possible, Al + Al (Al Holmes and Al Taylor) created a vibrant film to accompany the narration and full orchestra.

ABOUT BRIAN GREENE

Brian Greene is co-director of Columbia's Institute for Strings, Cosmology, and Astroparticle Physics (ISCAP), and is recognized for a number of groundbreaking discoveries in the field of superstring theory. His books—*The Elegant Universe*, *The Fabric of the Cosmos*, and *The Hidden Reality*—are widely read, inspiring *The Washington Post* to call Greene the "single best explainer of abstruse ideas in the world today." He has also had many media appearances, from Charlie Rose to David Letterman, and his three-part NOVA special based on *The Elegant Universe* won an Emmy Award and a Peabody Award. He is co-founder of the World Science Festival with Emmy award-winning television producer Tracy Day.

ADDITIONAL RESOURCES

worldsciencefestival.com/
Information about the full festival schedule, participants, and more.

worldsciencefestival.com/icarus
Information about *Icarus at the Edge of Time*, tickets, and teacher guidelines.

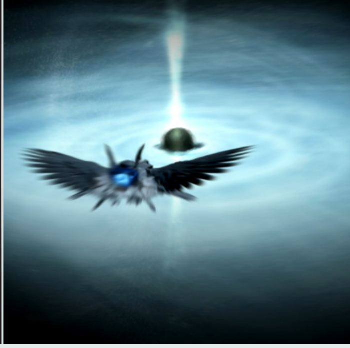
Monster of the Milky Way (NOVA):
nypl.org/locations/tid/65/node/58071
A NOVA episode about black holes.

ABOUT THE WORLD SCIENCE FESTIVAL

The World Science Festival is a production of the Science Festival Foundation, a 501(c)(3) non-profit organization headquartered in New York City. The Foundation's mission is to cultivate a general public informed by science, inspired by its wonder, convinced of its value, and prepared to engage with its implications for the future.

CORRELATION TO THE STANDARDS

Icarus at the Edge of Time and accompanying classroom activities can be correlated to the following standards for grades 5-8:



National Science Education Standards

A1: Abilities necessary to do scientific inquiry

A2: Understanding about scientific inquiry

B1: Properties and changes of properties in matter

B2: Motions and forces

B3: Transfer of energy

D3: Earth in the Solar System

G1: Science as a human endeavor

G2: Nature of science

New York State Intermediate Level Science Core Curriculum

Standard 4: Students will understand and apply scientific concepts, principles, and theories pertaining to the physical setting and living environment and recognize the historical development of ideas in science.

1.1b: Other stars are like the Sun but are so far away they look like points of light. Distances between stars are vast compared to distances within our solar system.

3.1h: Density can be described as the amount of matter that is in a given amount of space. If two objects have equal volume, but one has more mass, the one with more mass is denser.

5.2a: Every object exerts gravitational force on every other object. Gravitational force depends on how much mass the objects have and how far apart they are. Gravity is one of the forces acting on orbiting objects and projectiles.

New York City Science Performance Standards

S1b: Demonstrates understanding of position and motion and forces.

S3c: Demonstrates understanding of Earth in the Solar System.

S4d: Demonstrates understanding of impact of technology.

S4e: Demonstrates understanding of impact of science.

S5b: Uses concepts from Science Standards 1 to 4 to explain a variety of observations and phenomena.

S5f: Works individually and in teams to collect and share information and ideas.

S6a: Uses technology and tools to observe and measure objects, organisms, and phenomena, directly, indirectly, and remotely, with appropriate consideration of accuracy and precision.

BEFORE THE SHOW

Activity: Density

Visit *worldsciencefestival.com/Icarus* for more ways to teach the science of black holes.

Learning Objective:

To explore objects with different mass and volume in order to visualize and understand the principle of density (ratio of mass to volume).

Materials:

(per group of 4 students)

- ★ Scales
- ★ 5 large plastic cups
- ★ 5 different materials to be weighed (cotton balls, marbles, Legos, Styrofoam "peanuts," paper clips, pennies, etc.)

Instructions:

1. As a class, review the concepts of mass, volume and density.

2. As a group, predict which material will occupy the most space at one gram and which one will occupy the least. Record your results using the chart below. Next, measure one gram of each material and rank them according to their results. How accurate were your predictions? What do you notice about the volume of the different materials?

3. Now fill one cup full with each material. Before you weigh the cups, predict which materials will weigh the most and which the least. Then weigh the cups, record the masses, and rank them according to their results. How accurate were your predictions? What do you notice about the masses of the different materials?

4. As a class, discuss your results. How is the density of the materials related to their volume and mass? How would you rank the materials from least dense to most dense, and why?

Material	Predicted volume: Rank from least (1) to most (5)	Actual volume: Rank from least (1) to most (5)	Predicted mass: Rank from least (1) to most (5)	Actual mass: (in grams)	Actual mass: Rank from least (1) to most (5)	Density: Rank from least (1) to most (5)
A.						
B.						
C.						
D.						
E.						

BEFORE THE SHOW

Activity: Density

5. Dramatic density: Hold a cotton ball in your hand. Imagine that it weighs as much as the following:

- A baseball (142 grams)
- A small bowling ball (2.7 kilograms)
- An average-size man (65 kilograms)
- Earth (6,000,000,000,000,000,000,000,000 kilograms)

Density is one important factor in the creation of black holes. For Earth to become a black hole, it would have to be crushed to approximately the size of a cotton ball—the same mass at a much smaller volume with a much, much, much greater density!

BEFORE THE SHOW

Activity: Lifecycle of Stars

Learning Objective:

To explore the lifecycle of stars with different masses, and learn which stars become black holes.

Materials:

- ★ Balloons: 12 red, 12 yellow, 4 white, 2 blue (1 balloon per student for a class of 30)
- ★ White beads (place 1 inside each red or yellow balloon)
- ★ Marbles (place 1 inside each white balloon)
- ★ Ball bearings (place 1 inside each blue balloon)
- ★ Pin (to pop balloons)
- ★ Red, yellow, and black markers for writing on balloons

Instructions:

1. As a class, review how stars are born, the role of nuclear fusion in a star's core, and how stars vary from each other. Even though stars look similar in the night sky, they can differ from each other in their mass, size, temperature, color, brightness, age, distance from Earth, and what will happen to them when the fuel in their core runs out. A star's mass determines its temperature, color, and lifecycle. [See "Do Black Holes Actually Exist?" in the Teaching Guide]

2. The teacher will pass out the balloons, one to each student, and will tell everyone the approximate mass of their stars. Write down your predictions for the following:

- Which color star do you think is the hottest and which is the coolest?
- Which stars do you think will live the longest and why?
- Which stars will become black holes?

3. Model the lifecycle of a star by following the instructions below, depending on the color star you have. The teacher will call out the different "ages" so that all students can age their stars at the same pace.

BEFORE THE SHOW

Activity: Lifecycle of Stars

	Red Star: (2/5 the mass of the Sun)	Yellow Star: (same mass as the Sun)	White Star: (8x to 20x the mass of the Sun)	Blue Star: (over 20x the mass of the Sun)
Birth	Blow up to about 3” diameter	Blow up to about 3” diameter	Blow up to about 3” diameter	Blow up to about 3” diameter
5 million years	Stay as is	Stay as is	Stay as is	Blow up a little more
10 million years	Stay as is	Stay as is	Blow up a little more	Blow up as much as you can, and then pop it. Supernova explosion!
500 million years	Stay as is	Stay as is	Blow up a little more. As it expands, it cools (color it yellow).	Throw the balloon remnants into space, so that you’re left with only the ball bearing. A black hole!
1 billion years	Stay as is	Blow up a little more	Blow up as much as you can, and then pop it. Supernova explosion!	Black hole
5 billion years	Stay as is	Blow up a little more. As it expands, it cools (color it red). A supergiant!	Throw the balloon remnants into space, so that you’re left with only the marble. A neutron star!	Black hole
10 billion years	Stay as is	Blow up a little more, then cut up the balloon to show that the outer layer of the supergiant dissolves, creating a nebula.	Neutron star	Black hole
50 billion years	Blow up a little more	The nebula spreads out, so that you’re left with only the bead. A white dwarf!	Neutron star	Black hole
200 billion years	Deflate and remove the bead. The star dies, leaving behind a white dwarf!	The white dwarf burns out (color it black).	Neutron star	Black hole

This activity is modeled on one created by the Adler Planetarium (adlerplanetarium.org/educate/resources)

4. As a class, review the lifecycle of each of the types of stars modeled—when and how they expand, shrink, transform, etc. Discuss these questions: Which color star lived the longest and why? How did the actual results match your predictions? Which color stars became black holes? Why? What kind of star is our Sun? Will the Sun transform into a black hole someday?

ICARUS ACTIVITY GUIDE

AFTER THE SHOW

Activity: Black Holes and Time

Learning Objective:

To understand the effects of a black hole on time and space, and what would happen if you travel close to one.

Instructions:

1. As a class, discuss the following questions related to the show *Icarus at the Edge of Time*:

- What is gravity and how does it work?
- What did you know about black holes before the show?
- What did you learn about black holes from the show? What were you most surprised to learn?
- How does a black hole warp space and time?
- How do we know that black holes really exist?

2. In the show, as Icarus moved closer to the black hole, his father could see his actions slowing down more and more — a dramatic time dilation caused by the strong gravitational attraction of the black hole. To simulate the effect of time dilation, students will break into groups of at least four people each. Each group chooses a simple activity to perform, such as tying shoes, singing the ABCs, doing a short series of dance moves, etc.

3. Each group practices doing their activity, all students beginning at the same time, but at different speeds, as if they were at different distances from a black hole. The first student does the activity at a normal speed, the second one more slowly, the third more slowly still, and the fourth slowest of all.

4. After the groups have practiced, they present their simulations to the class as a whole.

5. As a class, discuss what you have learned about time dilation. Compared to how you experience time here on Earth, would someone in space experience it faster or slower? How about someone on the edge of a black hole?

ICARUS ACTIVITY GUIDE

AFTER THE SHOW

Activity: Envision a Black Hole

Learning Objective:

To use creative expression to imagine what it would be like to visit a black hole.

Instructions:

1. *Icarus at the Edge of Time* used film, music, and storytelling to imagine what a black hole is like. How would you envision a black hole — how it is born, how it warps time and space, how it gobbles up objects that come too close to it, etc.? Use music, dance, drama, or art to bring a black hole to life.

Students can do this project independently, in pairs, or in small groups.

2. Students should share their visions of black holes with the class. Afterwards, discuss the following questions:

- How were the visions of a black hole similar?
- How were they different?
- What do you find most interesting about black holes?

BONUS ACTIVITY

Activity: Travel into the Future

Learning Objective:

To use creative expression to imagine what it would be like to travel into the future

Instructions:

1. In the show, Icarus traveled into the future accidentally, because he had forgotten about the effect of the black hole's gravitational pull on time. But what if you yourself had the chance to travel to the future? Use creative writing to answer the following questions:

- Would you travel into the future?
- How far into the future would you go?
- What do you think the future would be like?

Your writing can be in the form of a poem, a story, or a diary of your trip to the future.