ASTROEDU

Peer-reviewed Astronomy Education Activities

Birth of a black hole

How are black holes formed?

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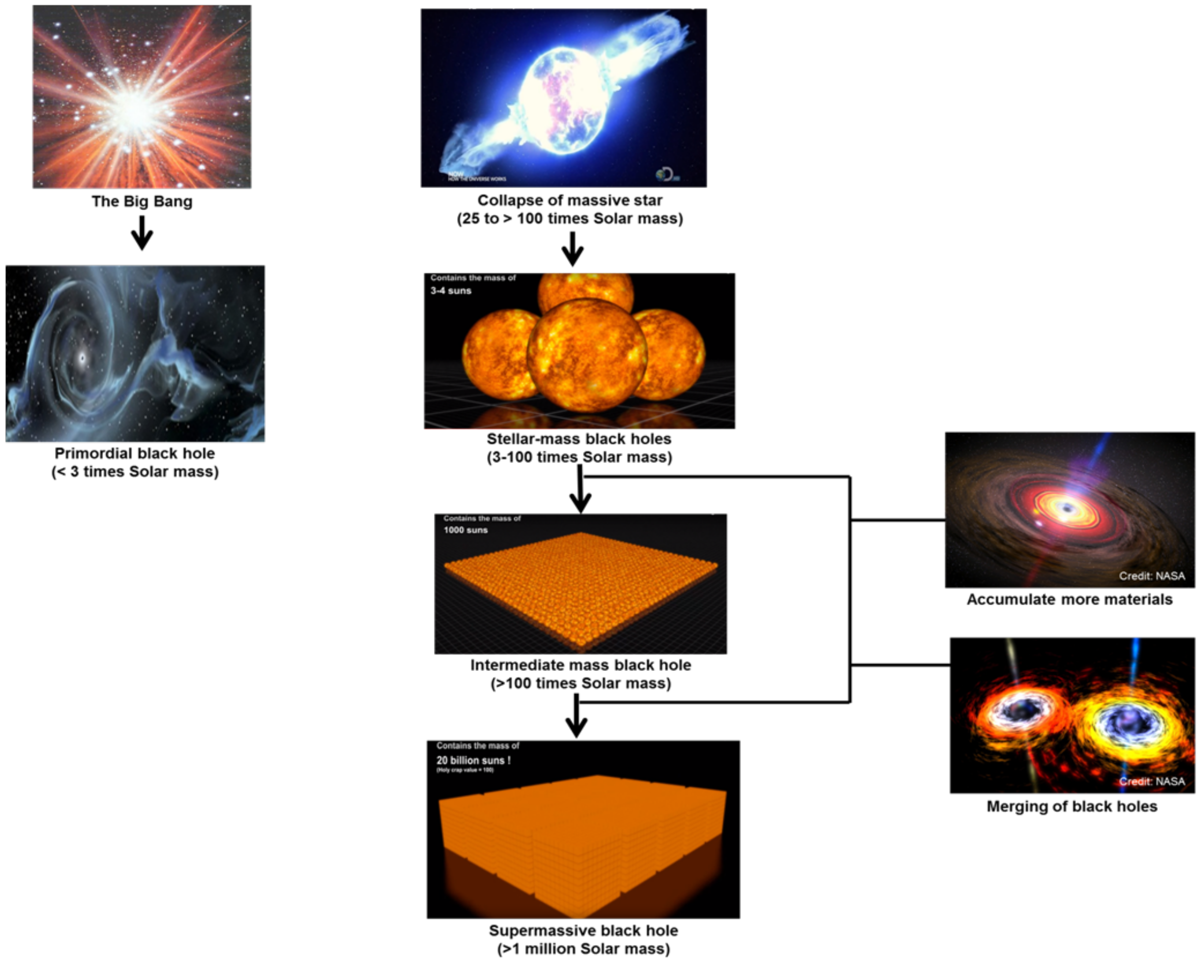
The Big Bang
Primordial black hole
(< 3 times Solar mass)
Collapse of massive star
(25 to > 100 times Solar mass)
Contains the mass of
3-4 suns
Stellar-mass black holes
(3-100 times Solar mass)
Contains the mass of
1000 suns
Intermediate mass black hole
(>100 times Solar mass)
Contains the mass of
20 billion suns !
Supermassive black hole
(>1 million Solar mass)
Credit: NASA
Accumulate more materials
Credit: NASA
Merging of black holes

AGE
14 - 19

LEVEL
Secondary

TIME
45min

GROUP
Group

SUPERVISED
No

COST PER STUDENT
Low Cost

LOCATION
Small Indoor Setting (e.g. classroom)

CORE SKILLS
Developing and using models, Planning and carrying out investigations, Constructing explanations, Engaging in argument from evidence

TYPE(S) OF LEARNING ACTIVITY
Guided-discovery learning, Interactive Lecture, Problem-solving, Debate, Discussion Groups, Puzzle-based learning, Modelling, Fun activity

KEYWORDS
Black hole, Gravity, Supernova, Puzzle

SUMMARY

GOALS

To understand how a black hole is formed, resulting in extreme gravity and that once something has fallen into the black hole it cannot escape.

LEARNING OBJECTIVES

- Students will explain how an area of strong gravity is created when a massive star collapses, resulting in a black hole.
- As students arrange the different black holes into the right order of the black hole formation and evolution, students will recognize that black holes have enormous mass and are categorized based on how much mass they contain.
- Students will practice logical thinking by deducing the order of events based on the given information.
- Students will practice giving arguments to explain one's idea or work.

EVALUATION

- During part 3 of the activity, ask the students to explain how black holes that are created as stars collapse come to have such extreme gravity. Students should relate their answers with the observation that the small dense marble that represents a black hole curves the stretchy sheet more (i.e. represents stronger gravity in the local area), as compared to the aluminum foil ball of similar weight to the marble but less dense.
- During the discussion in part 4, listen to the student explanations. Check if the students use the masses of different types of black holes as a piece of information to help them arrange the black holes in the right order in which they are formed and evolve.
- In part 4 of the activity, evaluate the logic and soundness of the students' discussion and explanation about how they deduce the order of events in black hole formation and evolution. Check whether they based their thinking on the information provided to them (in step 5 of part 4).

MATERIALS

- Round washing bowl (diameter minimum 30cm)
- Stretchy sheet (cut from stretchy fitted bed sheet)
- Elastic band (to fix the sheet on the wash bowl)
- 2 kinds of marbles: heavy and light weights.
- Aluminum foils
- Balloons
- Weighing scales
- PowerPoint presentation (attached supplementary material)
- Computer and projector for showing the presentation
- Student worksheet (attached supplementary material)
- Printed images (attached supplementary material)

BACKGROUND INFORMATION

Gravity

Gravity is a force that pulls objects together, bringing things together. Everything with mass has gravity. We perceive gravity as we jump up and get pulled down to the ground. Planets, stars, moons and other objects in the universe also have gravity. That's why they orbit around each other, like the Earth orbits the Sun, or the moon orbits around the Earth, instead of flying randomly off into space. That's why we see the moon and the Sun every day.

The more mass something has, the stronger the force due to gravity it produces. The Earth's gravity is stronger than the Moon's because it is more massive. So our bodies are pulled down on Earth more than if we were on the Moon. That's why astronauts can jump higher and more easily on the moon than on Earth. Our bodies also exert gravitational forces on other objects, but because our own mass is so small, the gravity from our bodies does not affect objects in any way we can easily see. The strength of gravity also changes with the distance to an object. The pull between the Earth and the moon is stronger than that between the Earth and Jupiter, despite Jupiter being extremely more massive than the Moon. This is because the Earth is closer to the Moon than to Jupiter.

Gravity was first described by Newton as a force. Described more than 300 years ago, Newton's theory of gravity is still applied today and it was used when scientists plotted the course to land man on the moon as well as to build bridges across rivers. Although Newton's theory describes the strength of gravity fairly accurately, he didn't know what caused gravity or how it worked. These concepts remained unknown for nearly 250 years, until Albert Einstein described gravity as a curvature of space. Space has 3 dimensions: up-down, left-right and forward-backward; and it can be visualized as a fabric, like a stretchy sheet. Any object with mass deforms space, just like a marble creating a dimple on the surface of the stretchy sheet. This curvature of space causes objects to interact with each other, often by moving towards each other, which is seen as gravity, a natural consequence of a mass's influence on the curvature of space. The more mass something has, the more the space is curved, and, therefore, the more gravity there is.

Life and death of a star

A star consists of many layers of gas. At the center of the star, a burning core exists, where nuclear fusion occurs and joins lighter elements together to form heavier elements. This process generates heat exerting an outward pressure, counteracting the force of gravity that pulls the gas towards the centre of the star. Stars spend most of their lives with these two forces in balance, maintaining its shape and size. You can visualize this process with a hot air balloon that needs the flame to keep the balloon inflated and floating. If the flame goes out, the balloon will collapse and fall from the sky, because there is no more hot air to keep the balloon inflated.

All stars start out fusing hydrogen into helium. Small, cool stars will stop soon after that and will not continue to fuse any other heavier elements. The very hot and more massive stars continue this fusing process to create more massive elements, not only burning hydrogen and helium but also carbon, oxygen and silicon. As the star reaches the end of its life, the nuclear fusion forms iron. Iron is a very stable element and does not easily fuse into heavier elements. Therefore, it requires much more energy to fuse than it can produce. Therefore, the iron core doesn't fuse into further elements, and the star stops producing energy. When the energy production stops, the force of gravity can finally overcome the outward push from the energy generated by the fusion. As a result, the heavy outer layers of gas of the star are unsupported and the star's core collapses, and in the resulting implosion, blowing apart the rest of the star. The explosion of a star is called supernova. All massive stars will end up this way at the end of their lives, but only the most massive of them will form a black hole.

Black hole formation

A black hole is a region in space where the pull of gravity is so strong that nothing, not even light, can escape. This is why a black hole is invisible. Black holes can be formed in a number of ways. Some black holes can be formed directly from very big stars, more than twenty five to hundreds times bigger than our Sun, when these stars collapse at the end of their lives. After a supernova event, the core of the massive star that is left over after the explosion is still too massive to support itself against gravity. Therefore, it continues to collapse causing all of this leftover mass to be compressed into a very small space, forming a black hole. These black holes, typically have mass 3 to 100 times the mass of the Sun, and are called stellar-mass black holes. It is thought that there are around 100 million stellar-mass black holes orbiting within our own galaxy.

After their formation, stellar-mass black holes can continue to grow as they accumulate more matter from their surroundings, such as other stars, gas and other black holes. If a black hole absorbs enough material, it can even grow to be more massive than a million Suns. These extremely massive black holes are called "supermassive black holes", and are the largest black holes. Supermassive black holes exist at the centres of most galaxies. One even exists at the centre of the galaxy that we live in, the Milky Way. It's believed that in the conditions of the early Universe, there were a lot of large, short-lived stars, therefore many stellar-mass black holes may have existed, which then gradually accumulated material and merged together over time, creating more massive black holes, eventually containing enough mass to be a supermassive black hole.

Black holes that have a mass in between the stellar and supermassive black holes are referred to as intermediate-mass black holes (IMBHs). Theoretically, these black holes should exist but scientists have not observed any of such black holes yet; at present there is only one good candidate, called HLX-1. IMBHs can be 100 to 100,000 times more massive than our Sun. It is proposed that IMBHs may form by feeding onto a stellar mass black hole, or by the merger of many stellar-mass black holes.

In theory, black holes less massive than stellar-mass black holes may also exist. These are called primordial black holes or mini black holes. They are the smallest black holes. It is believed that they may have been created soon after the Big Bang, where the enormous pressures and temperatures required for the formation of such a small black hole were present. However, these mini black holes are yet to be observed.

Where does a black hole’s extreme gravity come from?

A black hole is much smaller in size than what would be expected from the enormous mass that it can contain. For example, primordial black holes would be the size of an atom but the mass of a large mountain. Supermassive black holes that have the diameter of our solar system but the mass more than millions Suns. When such enormous mass is compressed into a tiny space, space becomes extremely curved (like a deep well). If another object gets close enough to the concentrated mass, space becomes very curved and, therefore, gravity is extreme. In such extreme gravity, once an object falls into the well it becomes trapped. In contrast, when the same mass is larger in size, gravity isn’t so extreme because the object’s mass is spread out over a larger area, curving space more gradually (like a shallow pit), and the force of gravity is less extreme. Because the enormous mass of black hole is extremely concentrated, it warps space so much that everything, once entered, cannot escape from the gravitational pull or well, not even light. Black holes do not necessarily have more mass than everything else in the Universe but the compression of its mass into a small area creates its extreme gravity.

FULL ACTIVITY DESCRIPTION

<iframe width=”560” height=”315” src=”https://www.youtube.com/embed/4pX5WH8P4IU” frameborder=”0” allow=”accelerometer; autoplay; encrypted-media; gyroscope; picture-in-picture” allowfullscreen=””“>

Figure 1: Aluminum foil balloon

1. Tell the students that the inner aluminium foil and the balloon is the core of the star. The outer aluminium foil is a layer of gas. Use the background information to explain that this gas layer is maintained on the surface, holding the star's shape, because of the burning core. This burning creates a pressure that pushes the gas outward. In this activity, the air in the balloon pushes outward, representing the pressure generated by the burning.

2. Explain to the students that opposing this outward push is gravity. Gravity causes the gas to be pulled inwards. Students then use their hands to gently squeeze the foil-covered balloons, imitating the effect of gravity, which pulls the gas towards the centre of the star. But the balloon does not collapse. Students try to explain why this is the case; this is because of the air in the balloon pushing outward.

Figure 2: Hands compressing aluminum foil balloon

3. Tell the students that throughout a star's life, the outward force generated by burning within the star balances the inward force of gravity. Therefore, the star does not collapse due to gravity when burning is occurring. Ask students to record the initial mass of this aluminum covered balloon.

Figure 3: Aluminium foil balloon - Initial weight

4. Explain that at the end of the star's life, it runs out of fuel to burn in its core and burning stops. This is like popping the balloon (use a sharp pin). At this step, retain the foil in its original shape around the balloon.

5. Relating to the balloon in the activity, students should predict what happens to the star under the effect of gravity now that burning has stopped. Since there's no longer an outward push from within to support the star, gravity now wins and the star collapses. Just like the balloon-aluminum foil can now be compressed with hands.
6. Use the background information to explain that as a star collapses, the gas layer (outer aluminum foil) is blown away. The leftover core is still too massive, but gravity collapses it further, compressing all of the mass into a smaller and smaller area.
7. Students remove the outer aluminum foil (it gets blown away), leaving the inner foil representing the star's core. Students then use their hands to act as gravity, pushing inward and squeezing the remaining 'core' aluminum foil into a smaller ball (representing a black hole).

8. Students then measure the mass of the crumpled aluminum foil (which now represents a black hole) and compare that result with the initial mass (the star) that they recorded. They should realise that the black hole still contains a lot of mass of the star, but has lost some during the process.

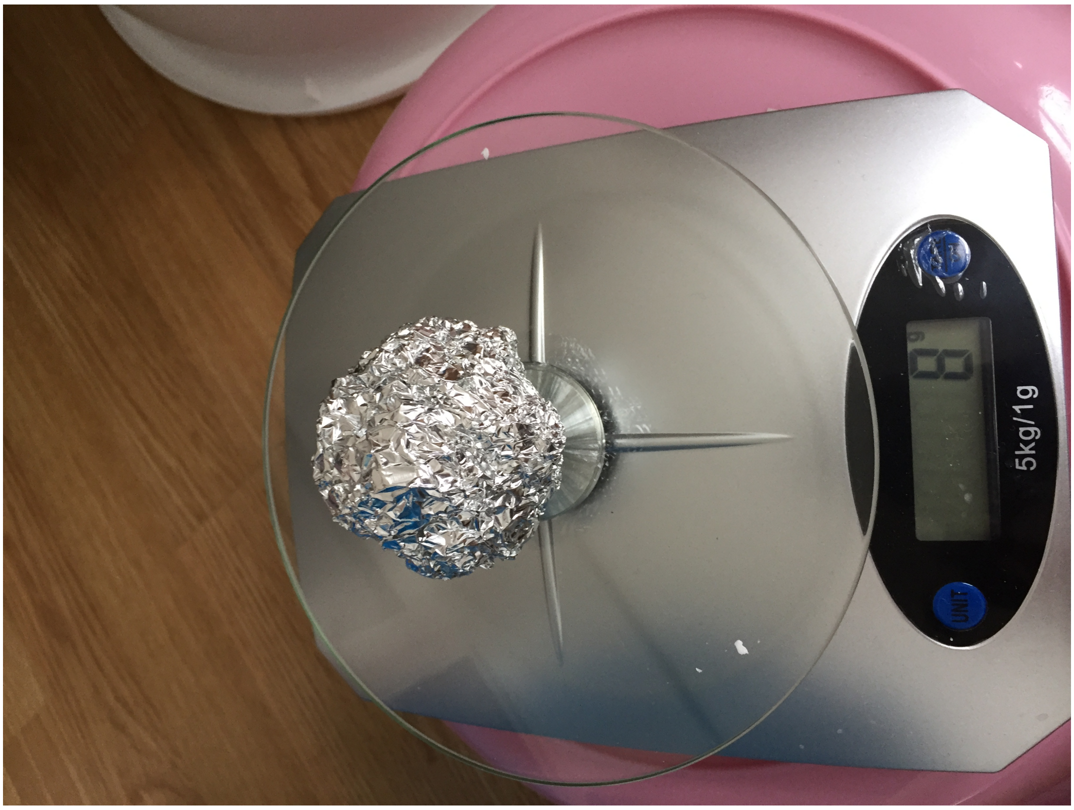

Figure 4:Aluminium foil balloon – weight after collapse

9. Students discuss which one is more dense, the initial star or the black hole. The black hole is smaller but it still contains a lot of the mass of the initial star, so it is more dense because the mass is concentrated in a smaller volume.

10. Conclude the activity by discussing with the students that the collapse of the star into such a small region of space results in a black hole, with extreme gravity, where the black hole will capture anything that comes too close. To understand how gravity is so extreme in black holes, students might first need to recap what gravity is, which is outlined in the next activity.

Part 2: Gravity (7 min)

1. Use the background information to explain the concept of gravity as an attractive force and that this attraction can be explained as a result of space being bent by the mass of an object.
2. Place a stretchy sheet on a large round bowl. Introduce the surface of the sheet as a small portion of space and point out that this is only space in 2 dimensions because space surrounds us everywhere in all directions.
3. Students then place a heavy marble on the sheet and observe there is a curvature due to the marble. Then they roll a lighter marble on the sheet so that the light marble moves toward the heavier one and circles around it. An object bends space like the marble does to the stretchy sheet, causing objects to move towards each other. This effect is called gravity, which is the curvature of space.

In space, the stars and planets do not generally collide as seen with the marbles in the activity. This is due to friction of the marbles with the fabric, but there is no such fabric in space. Gravity holds planets and stars in orbit to each other.

Figure 5: Gravity – stretchy sheet and marbles

Part 3: How does black hole create enormous gravity? (7 min)

1. As the students have understood gravity as space curvature, they now investigate how gravity in black holes is so extreme. Ask the students to recap how a black hole is created from the initial star. Answer: it is the concentration of mass into tiny space. Show the students the heavy marble as the black hole and a large ball of the same mass as the marble to represent the initial star (like in activity 1). Have the students confirm the two have similar weights.
   If a larger ball is not available, prepare in advance an aluminum foil ball with some weights (e.g. marbles) inside to have the same weight to the black hole marble.
2. Students place the initial star (large ball) on the stretchy sheet and compare its curvature with the curvature created when replacing it with the black hole marble. The curvature created by the large ball is less steep than that created by the black hole marble.

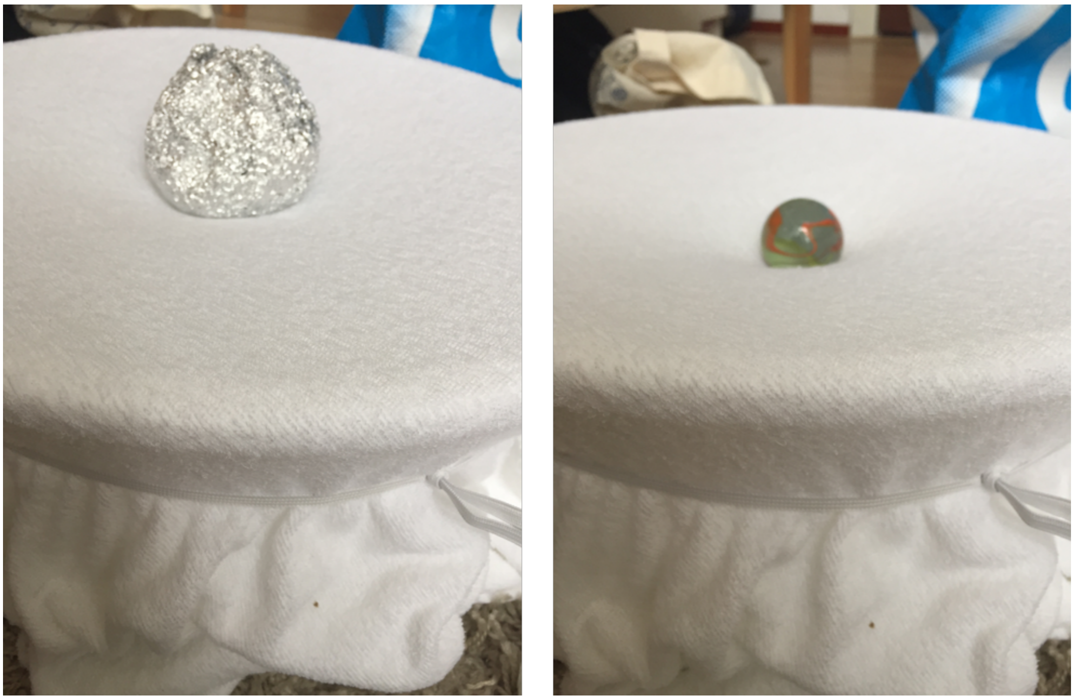

Figure 6: Comparing curvature created objects different in density

3. Ask the students to relate this observation to explain how the black hole created from the collapse of a star has extreme gravity. Help the students (if needed) by telling them to relate the density of the objects with the space curvature it creates. Because a black hole is denser, the mass of the 'black hole' marble is compressed into a smaller space, instead of spreading out as much as the large sphere, it creates steeper space curvature.
4. Confirm with students that this experiment shows how the gravity of a black hole is so extreme. The small size of a black hole allows an object to get very close to it, to an area where space is greatly curved. Therefore the object, at this point, experiences the extreme gravity of the black hole and gets pulled in.

Part 4: Which stars can become a black hole? The evolution of a black hole (10 min)

1. Use the accompanying slideshow (if possible) to show students the size of the Earth compared to the Sun and that only stars that are massive enough, at least twenty five times more massive than the Sun, can become a black hole when they collapse.
2. Use the accompanying slideshow (or printed image) and show students that there is a supermassive black hole at the centre of our Milky Way galaxy. Tell students that this black hole has a mass of more than a million suns.

3. The students should work in groups to solve a puzzle of events to reorder the formation of black holes and evolution to supermassive black holes. Present to the students this blank flow chart. Print out a set of 8 accompanied images for each group for this activity.

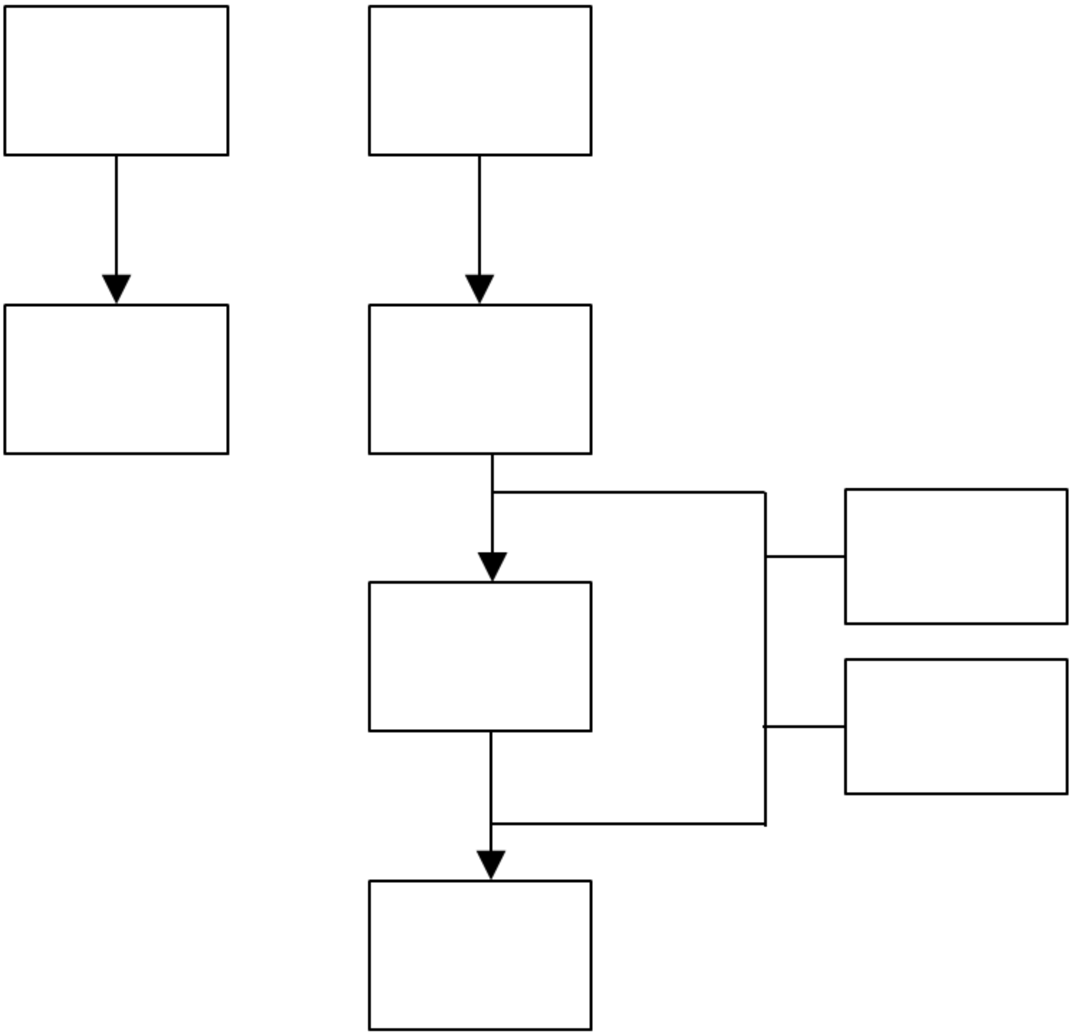

Figure 7: Blank flow chart - Black hole formation and evolution events

4. Have the students discuss in their groups to arrange the flowchart in the correct order. Once finished, have all student groups present their arrangement on the board and explain their flowchart. If there's a difference between the groups, all groups should discuss together and give arguments to explain their work.

5. The correct flow chart is shown below. You can provide some hints for students to help them get started (if necessary):
6. Remember that only stars, twenty five to hundreds of times more massive than our Sun, could collapse into a black hole.

7. As the star is blown apart when it collapses, it loses some mass and the leftover mass is compressed to become a black hole.

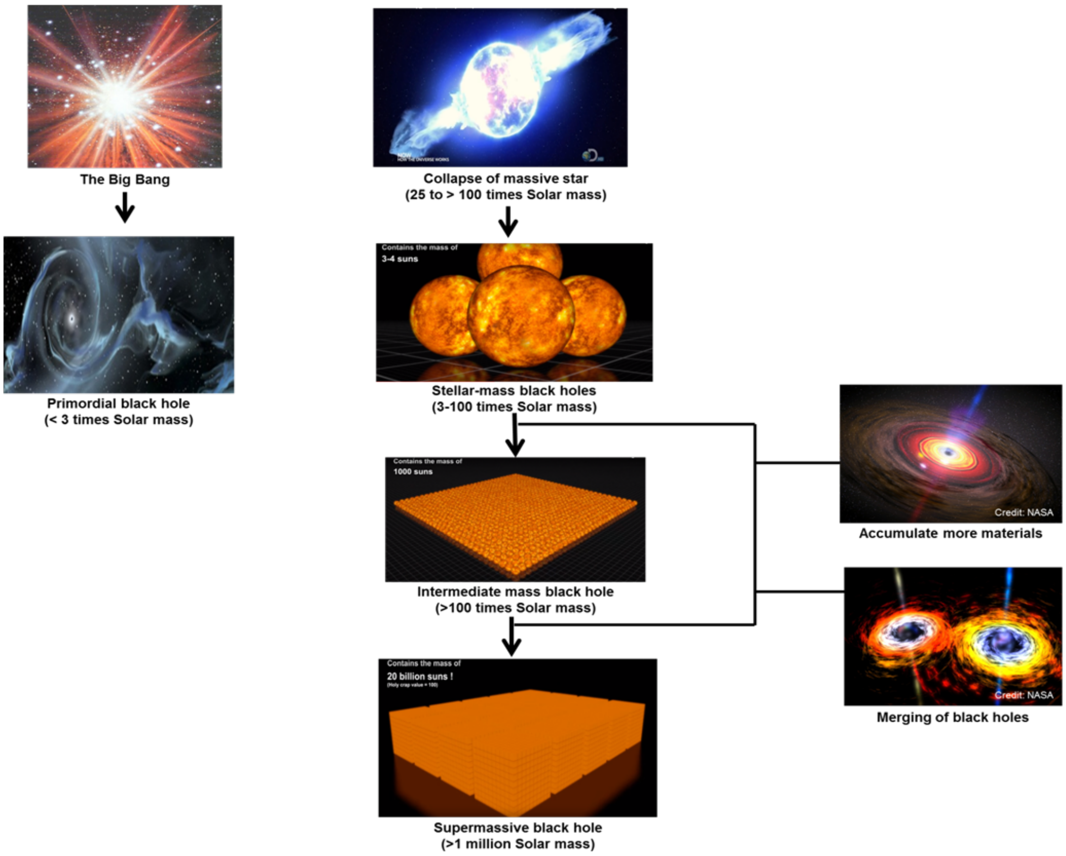

Figure 8: Completed flow chart - Black hole formation and evolution events

8. Go through the flow chart with the students. Using the background information to explain further about the types of black holes.

9. Conclude that black holes can consume huge amounts of matter and contain a very large mass, despite being small in size.

CURRICULUM

ADDITIONAL INFORMATION

The use of stretchy sheet and marbles are based on previous Astroedu activity ‘Model of a black hole’. Activities about gravity and collapse of star to a black hole are inspired by Inside Einstein’s Universe website.
For students to know more how a black hole can be detected, see Activity “Hunting for black holes” (15-18 year-old level).
For students to know what happen when a black hole eats material from its surrounding, see Activity “Feeding black holes and what happen to the Universe?” (15-18 year-old level).
For students to understand how black hole gets extreme gravity and captures anything that come too close, see Activity “What is a black hole?” (15-18 year-old level).

CONCLUSION

In this activity, students use a balloon and aluminum foil to understand how a massive star can collapse into a black hole and how the created black hole has extreme gravity, such that everything that falls into it cannot escape, even light. Students also learn how different types of black holes are created, but all contain enormous mass and have the capacity to consume even more.

ATTACHMENTS

- Images for printing
- Student worksheet
- Presentation

ALL ATTACHMENTS

All attachments

CITATION

Han Tran; Thomas Russell, 2018, *Birth of a black hole*, astroEDU,

ACKNOWLEDGEMENT

Pedro Russo