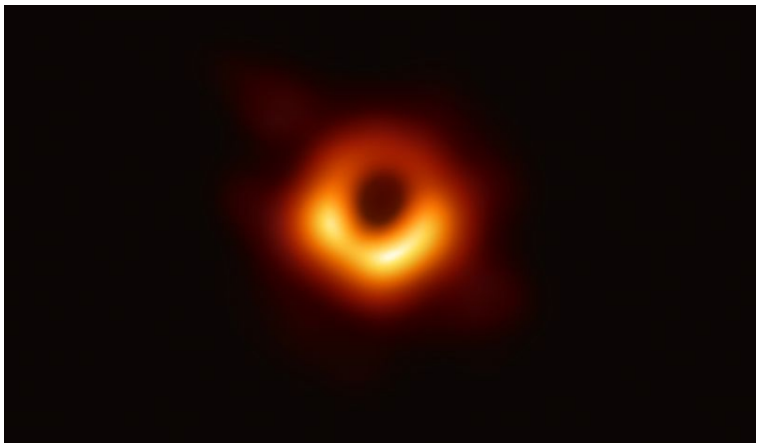


Testing Einstein's Gravity with Black Holes

Pierre Christian

Teen Astronomy Cafe Oct 2019

A little bit about myself

A little bit about myself

A little bit about myself

A little bit about myself

A little bit about myself

Images credit: The Jakarta Post

A little bit about myself

Why did I choose to be an astrophysicists?

A little bit about myself

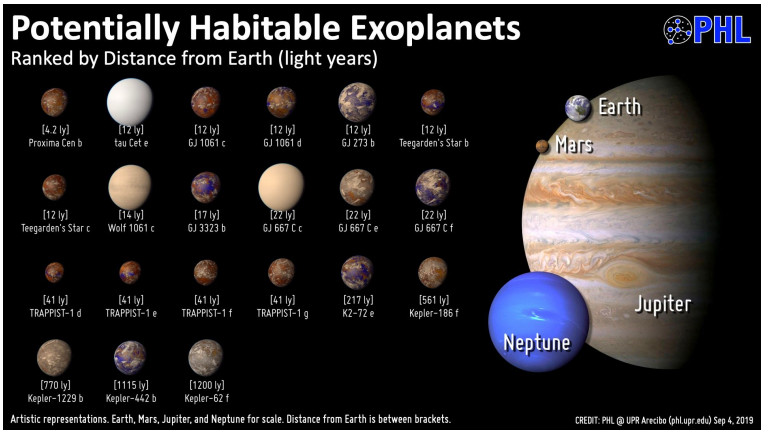
Why did I choose to be an astrophysicists?

The most interesting things are in space!

A little bit about myself

Why did I choose to be an astrophysicists?

The most interesting things are in space!



Exoplanets: Alien worlds outside our solar system

Image credit: Planetary Habitability Laboratory, University of Puerto Rico

A little bit about myself

Why did I choose to be an astrophysicists?

The most interesting things are in space!

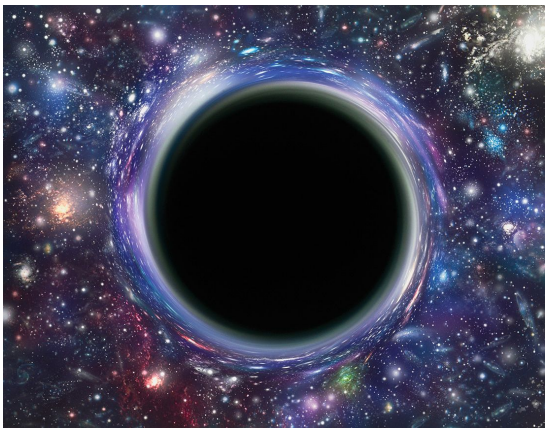
Galaxies: Conglomeration of many billions of stars

Image credit: Robert Gendler

A little bit about myself

Why did I choose to be an astrophysicists?

The most interesting things are in space!



Black Holes

Image credit: Mehau Kulyk

A little bit about myself

Why did I choose to be an astrophysicists?

The most interesting things are in space!

Warning: Artist rendition, **not** a real black hole!

Black Holes

Image credit: Mehau Kulyk

Part I: What are black holes?

What are black holes?

Our current theory of gravity is **general relativity**
-) Proposed by Albert Einstein (1879-1955)

In **general relativity**, even light is affected by gravity

Prior to the early 20th century, the accepted theory of gravity is what is called Newtonian Gravity. This theory asserts that gravity is a force that an object exerts on another, with the magnitude of said force being proportional to the masses of the objects. In the early 20th century, Albert Einstein introduced a new theory of gravity, called “general relativity”. This theory supplanted Newtonian Gravity as the most accurate theory of gravity known to humanity. More of the history can be read on wikipedia: https://en.wikipedia.org/wiki/History_of_general_relativity

A black hole is a gravitational object that cannot be explained by Newtonian Gravity, but must be analyzed using general relativity. The only two points about general relativity that is important to understand for the rest of this presentation is that: 1) in general relativity, even light is affected by gravity (even if they’re massless) and 2) in general relativity, nothing can travel faster than light in vacuum.

The main point of slides 14-20 is that: if light is indeed affected by gravity, could it be that (much like a ball that falls back down to a planet when thrown), that light can also be similarly trapped?

What are black holes?

Our current theory of gravity is **general relativity**
-) Proposed by Albert Einstein (1879-1955)

In **general relativity**, even light is affected by gravity

If I throw a ball from the surface of a planet, it will fall back down due to gravity

What are black holes?

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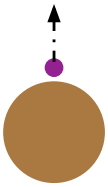

What are black holes?

Our current theory of gravity is **general relativity**
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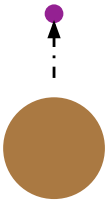
In **general relativity**, even light is affected by gravity

If I throw a ball from the surface of a planet, it will fall back down due to gravity



What are black holes?

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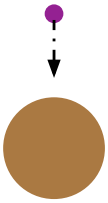
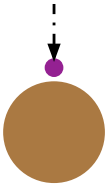


What are black holes?

Our current theory of gravity is **general relativity**
-) Proposed by Albert Einstein (1879-1955)

In **general relativity**, even light is affected by gravity

If I throw a ball from the surface of a planet, it will fall back down due to gravity



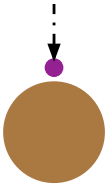
What are black holes?

Our current theory of gravity is **general relativity**
-) Proposed by Albert Einstein (1879-1955)

In **general relativity**, even light is affected by gravity

If I throw a ball from the surface of a planet, it will fall back down due to gravity

Question: If light is affected by gravity, can there be objects where light also falls back down due to gravity?



What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

-) The “denser” a planet, the stronger the gravity

One key aspect that I did not put on the slide is that the denser the planet, the stronger the gravity ON ITS SURFACE. This is why the earth that is squeezed Earth on slide 24 has “stronger gravity” -- I meant that according to a person standing on its surface, it has stronger gravity.

What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

-) The “denser” a planet, the stronger the gravity

Image credit: NASA

What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

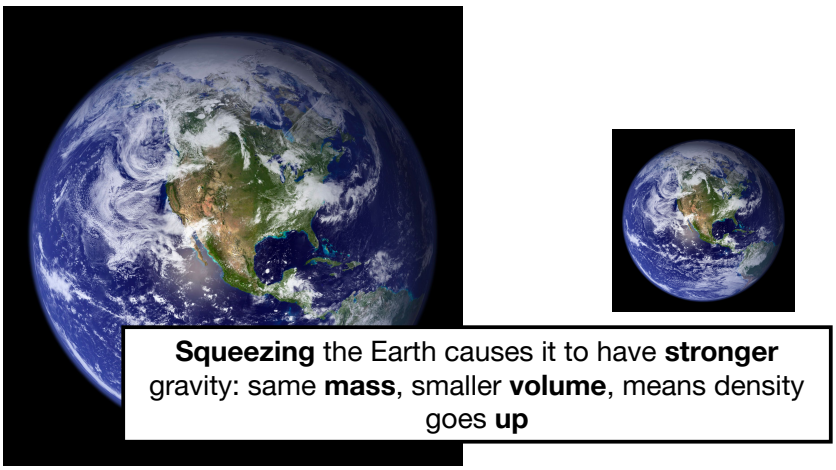
-) The “denser” a planet, the stronger the gravity

Image credit: NASA

What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

-) The “denser” a planet, the stronger the gravity



Squeezing the Earth causes it to have **stronger** gravity: same **mass**, smaller **volume**, means density goes **up**

Image credit: NASA

What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

-) The “denser” a planet, the stronger the gravity
-) The object that can trap light must be **extremely** dense!

The point of slides 25-28 is that if it is true that:

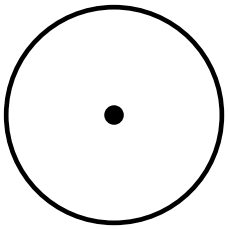
1) The denser an object is, the stronger is its gravity (on its surface), and
2) light is the fastest thing there is (i.e., it is the most difficult thing to trap using gravity)

Then an object that can trap light must be extremely dense! This extremely dense object is called the “singularity”. Intuitively (though not formally correct), this “singularity” is infinitely dense.

What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

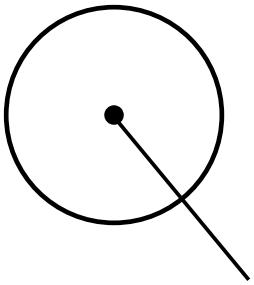
-) The “denser” a planet, the stronger the gravity
-) The object that can trap light must be **extremely** dense!



What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

-) The “denser” a planet, the stronger the gravity
-) The object that can trap light must be **extremely** dense!



Singularity: A point of infinite “density”

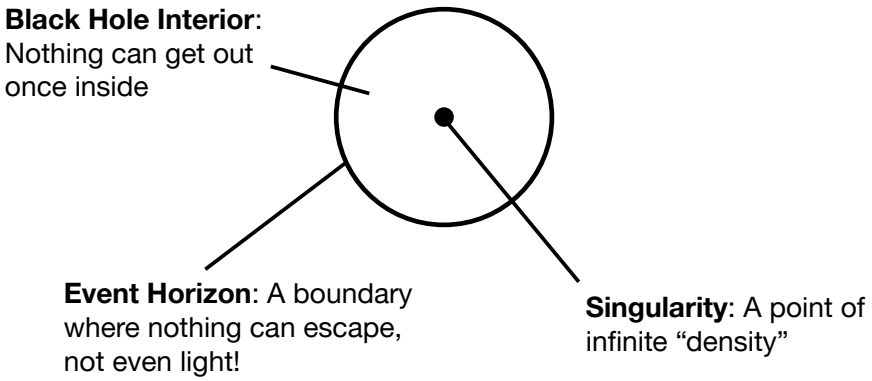
NSF | NOIRLab

Speaker Notes for Black Hole Orbits

What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

-) The "denser" a planet, the stronger the gravity
-) The object that can trap light must be **extremely** dense!



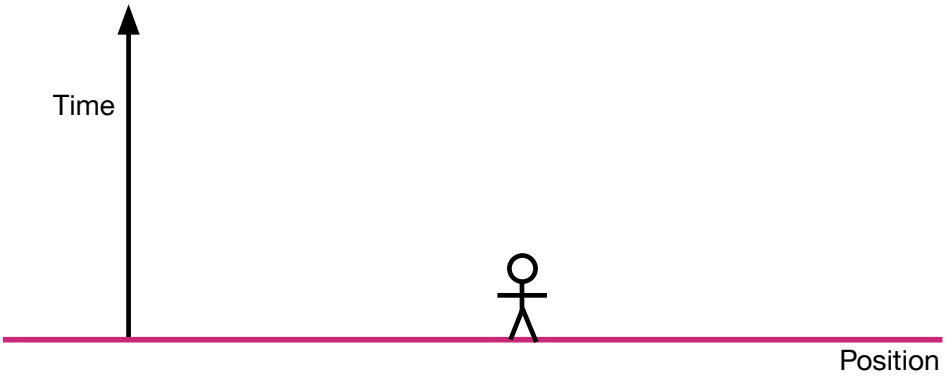
It turns out that once you have a singularity, an "event horizon" is formed. An event horizon is a sphere around the singularity where anything that fall inside it is trapped inside, not even light can escape this prison!

A black hole is a singularity surrounded by an event horizon.

On slides 29-53, we will explain why this event horizon forms around a singularity.

What are black holes?

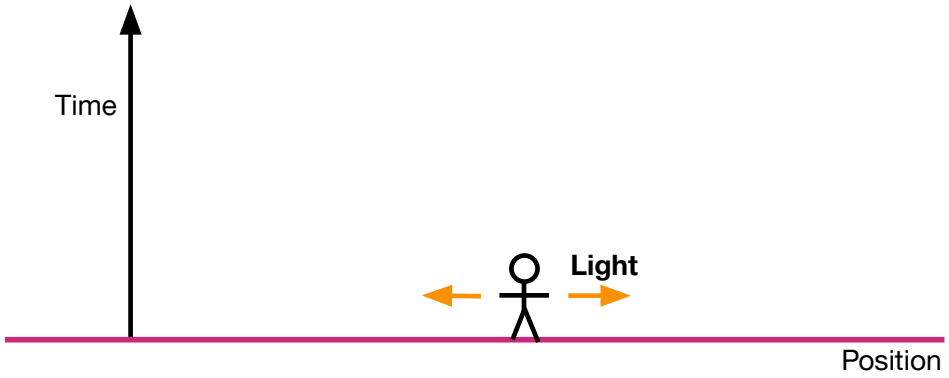
Black hole: A region of such strong gravity that even light cannot escape



To get a better understanding of black holes, consider the following picture

Slides 29-41 describes the fact that:
Because nothing can travel faster than light, we are always trapped within this “causal cone”. There is no black hole yet in this picture. I am not trapped because there is a black hole, but simply because I cannot travel faster than light.

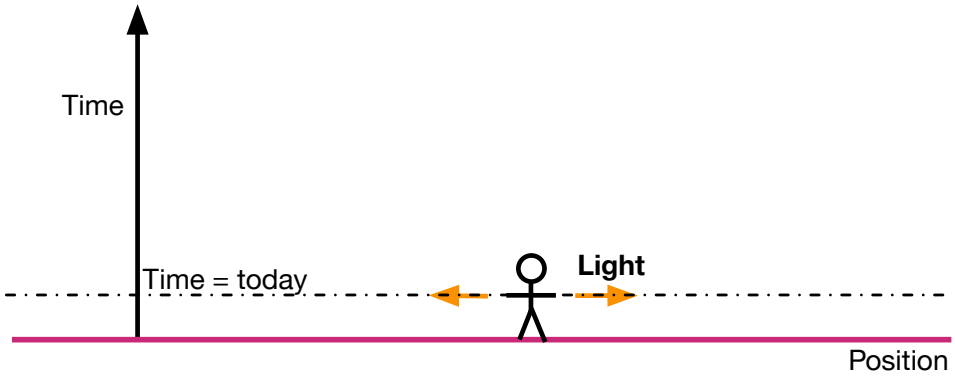
What are black holes?



I, standing on a flat plane, shoot two beams of light going opposite directions, **no** black hole yet in this picture!

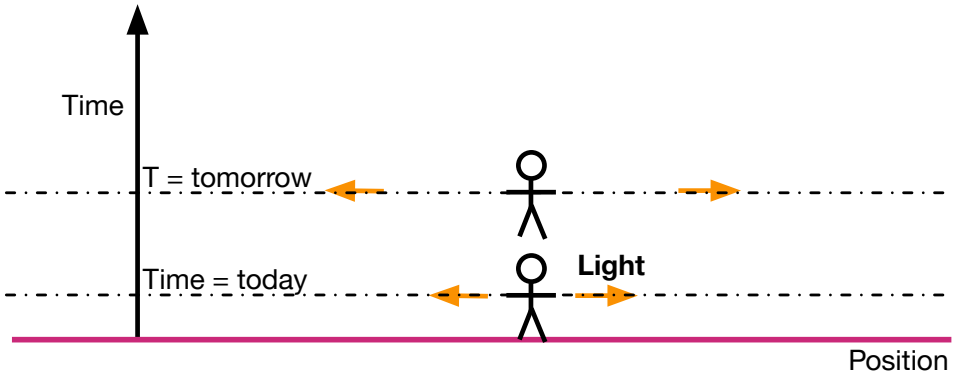
The yellow arrows are the two beams of light. The x axis is position, and the y axis is time.

What are black holes?



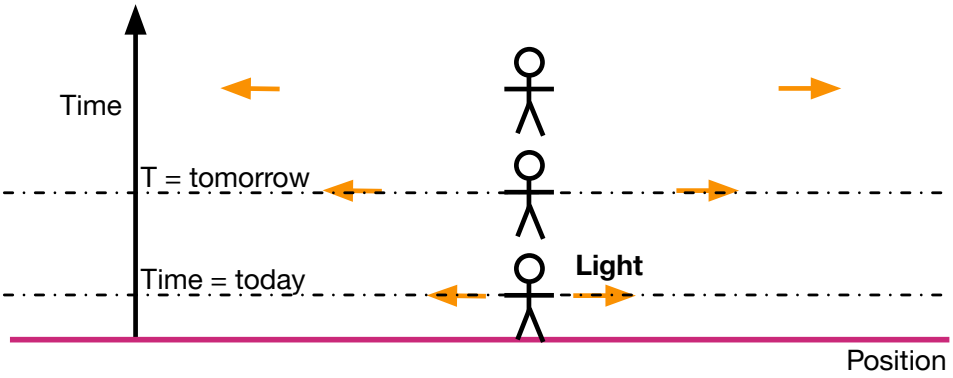
I, standing on a flat plane, shoot two beams of light going opposite directions, **no** black hole yet in this picture!

What are black holes?



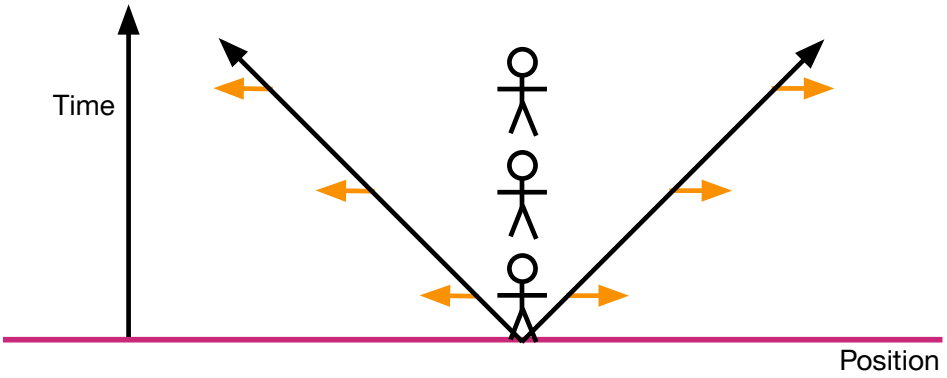
The light beams travel away from me at the speed of light

What are black holes?



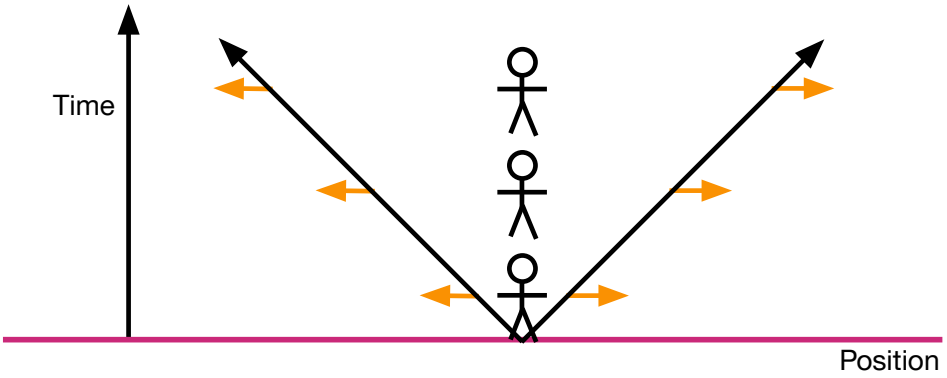
The light beams travel away from me at the speed of light

What are black holes?



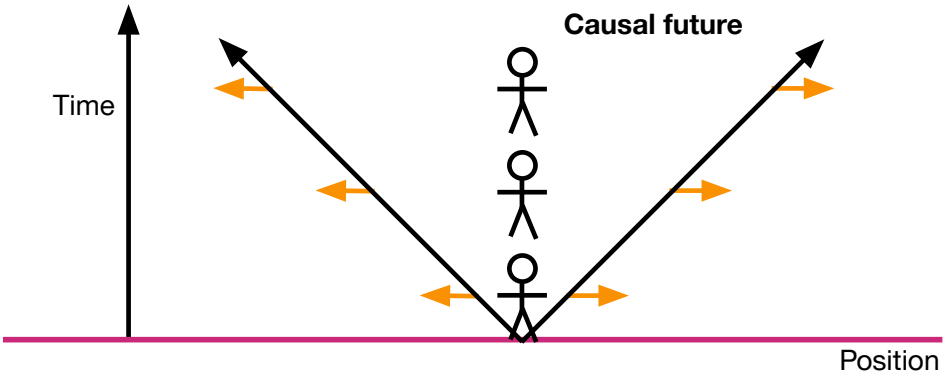
This triangle (black arrows) is formed by connecting the yellow arrows. This triangle (actually a cone as we live in 3 dimensions) represents where the beam of light is at a given time -- this cone is called the ‘causal cone’. Because I cannot move faster than light, I cannot move outside of this triangle.

What are black holes?



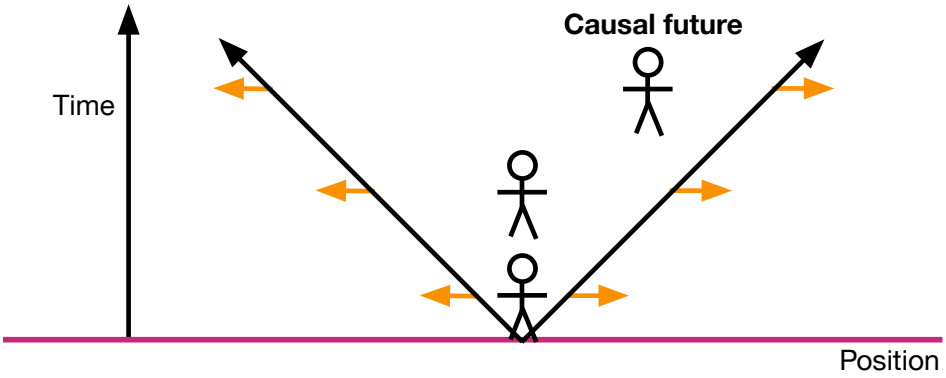
Nothing can travel faster than light (postulate of relativity)

What are black holes?



Nothing can travel faster than light (postulate of relativity)
-) I can only move within these lines
-) Everything that I can affect is within these lines (**causal cone**)

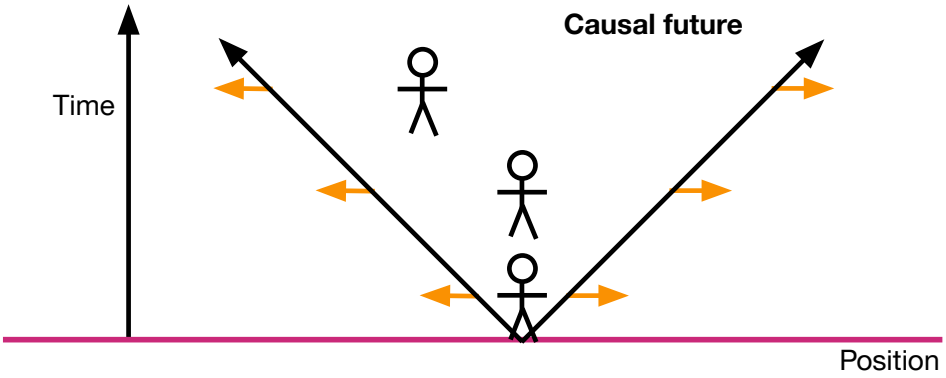
What are black holes?



Nothing can travel faster than light (postulate of relativity)
-) I can only move within these lines
-) Everything that I can affect is within these lines (**causal cone**)

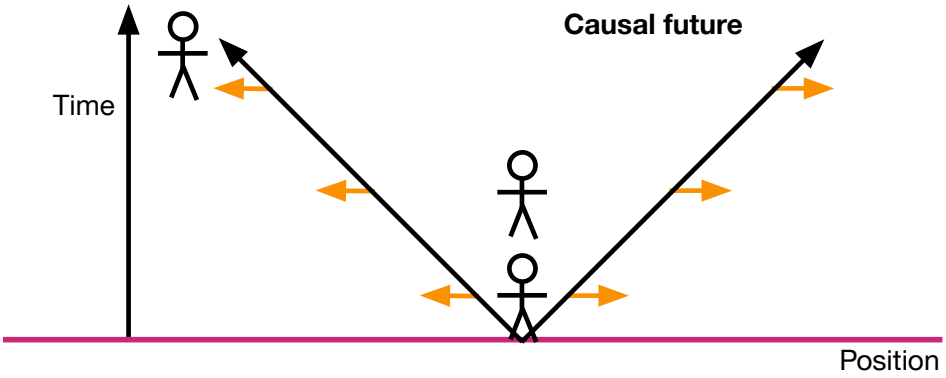
In slides 37-41, I gauge the understanding of the audience by asking whether I can move to the position shown in slide 37 and 38 (answer is yes, because I'm inside the causal cone) and whether I can move to the position shown in slide 39 (answer is no, because I would've been outside the causal cone).

What are black holes?



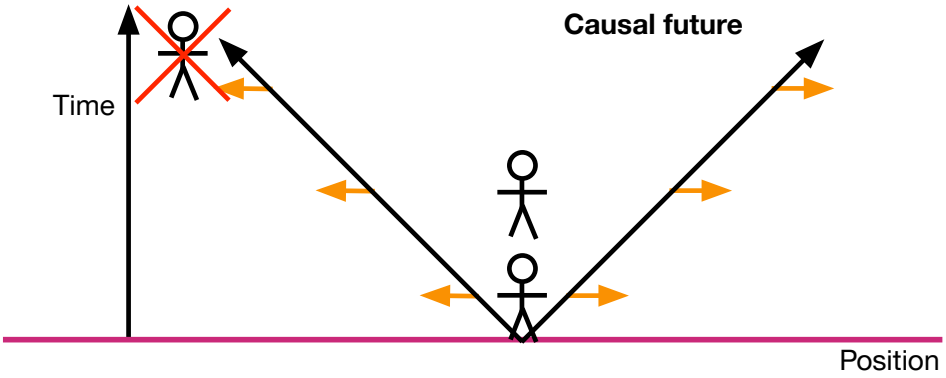
Nothing can travel faster than light (postulate of relativity)
-) I can only move within these lines
-) Everything that I can affect is within these lines (**causal cone**)

What are black holes?



Nothing can travel faster than light (postulate of relativity)
-) I can only move within these lines
-) Everything that I can affect is within these lines (**causal cone**)

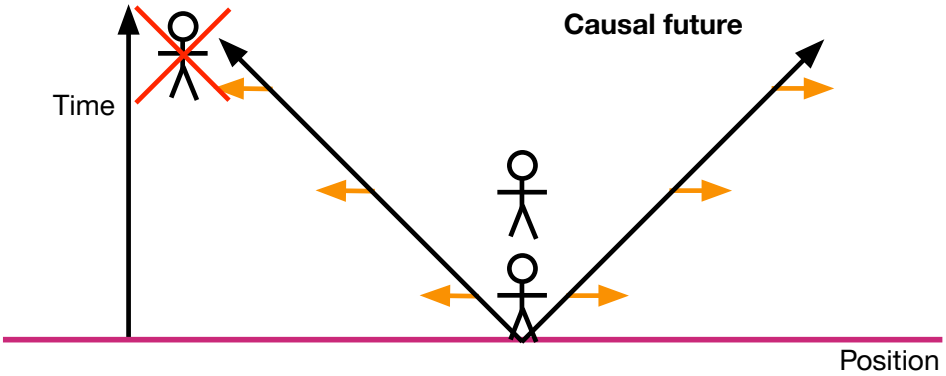
What are black holes?



Nothing can travel faster than light (postulate of relativity)
-) I can only move within these lines
-) Everything that I can affect is within these lines (**causal cone**)

I **cannot move here** because to do so I need to travel faster than light!

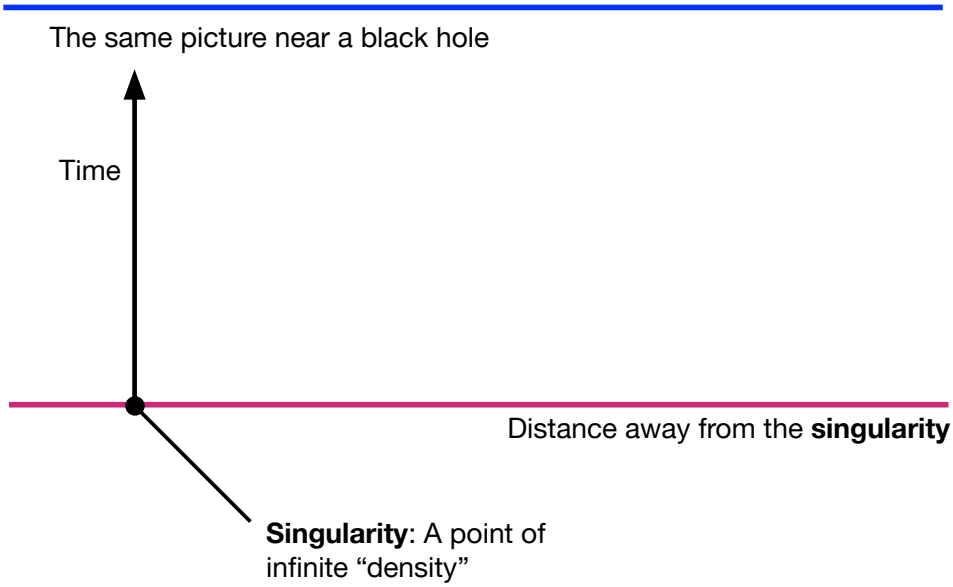
What are black holes?



Remember, there is **no** black hole yet in this picture! I am trapped Inside these lines not because there is a black hole, but because I cannot move faster than light!

I **cannot move here** because to do so I need to travel faster than light!

What are black holes?



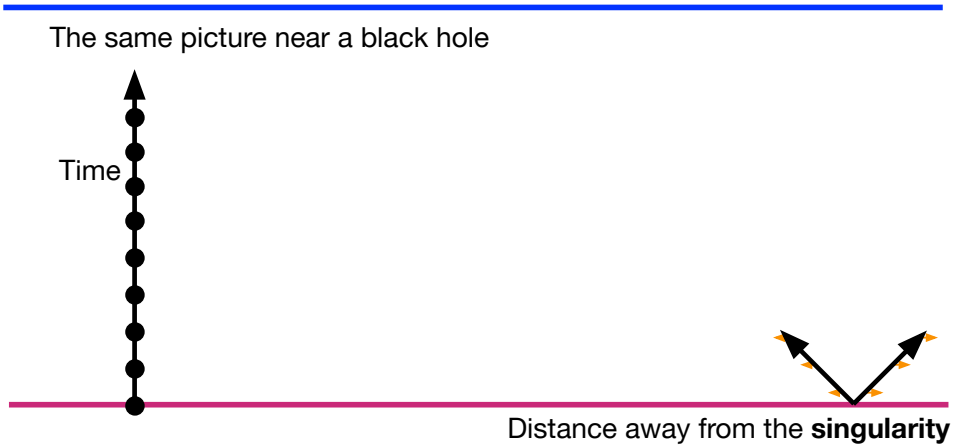
Now we are drawing the causal cone near a black hole. Slide 42-52 will show how the event horizon of a black hole forms around a singularity.

What are black holes?

The same picture near a black hole

The singularity does not move, so it just goes up in time

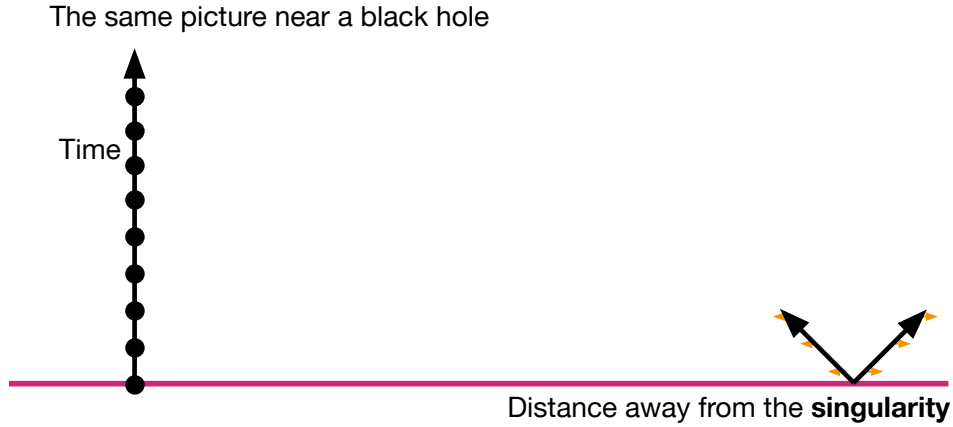
What are black holes?



Far from the singularity (far from the black hole), my causal cone looks the same as before

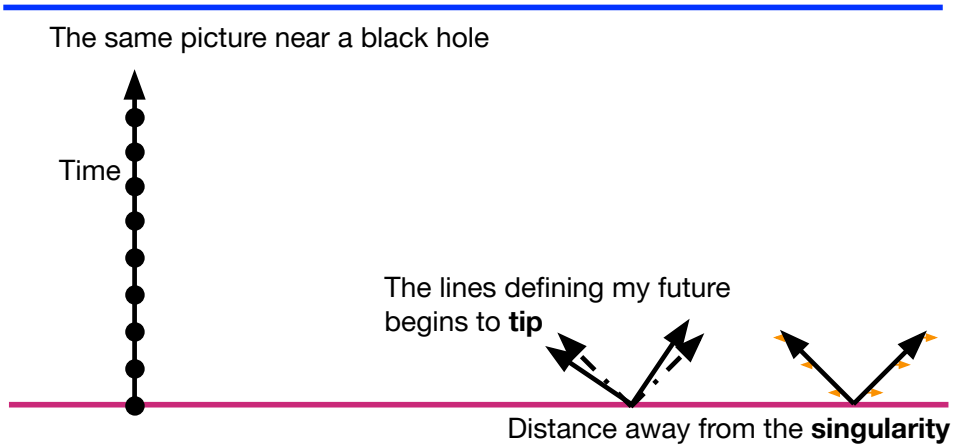
Far from the singularity, we don't feel its gravitational effects (because gravity gets weaker with distance), so at this distance the causal cone should look identical to the one without a singularity.

What are black holes?



In general relativity, **light** is affected by gravity!

What are black holes?

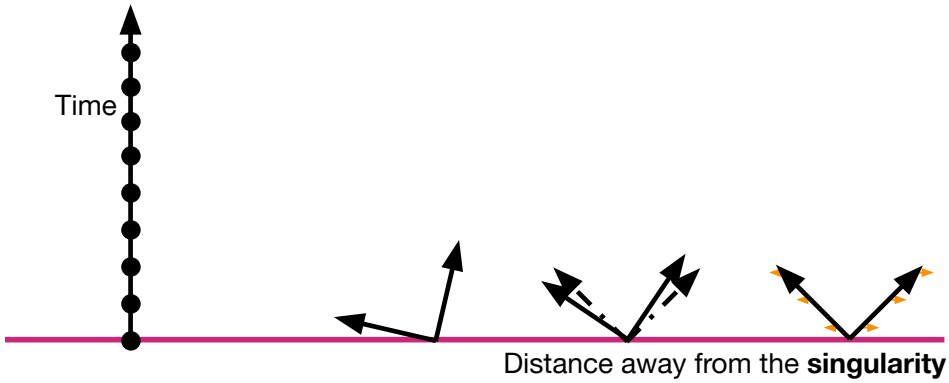


In general relativity, **light** is affected by gravity!

Remember, the causal cone is ‘made of light’, or more accurately, it just labels where a light beam. Because light is affected by gravity, this cone that is made of light is going to be attracted to the gravity of the singularity, and will tip towards it (the same behavior as if this cone is made of metal instead of light, both of them are affected by gravity!).

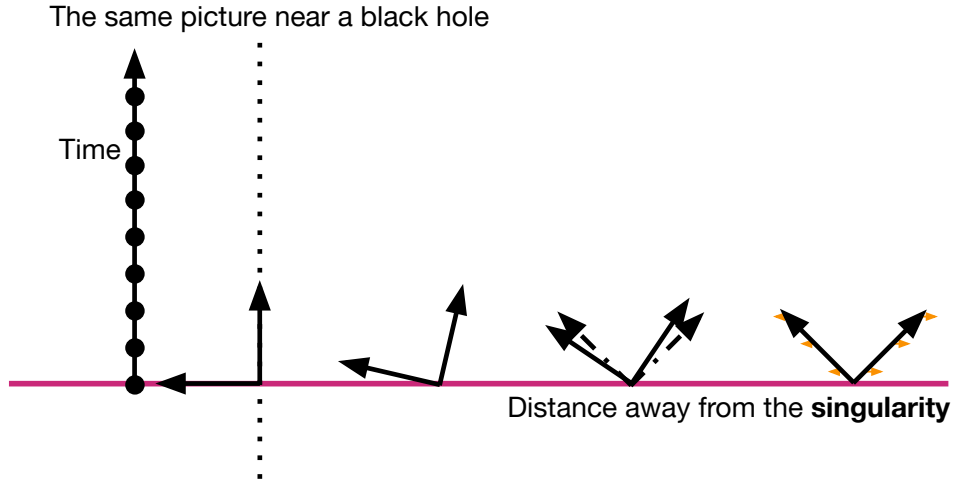
What are black holes?

The same picture near a black hole

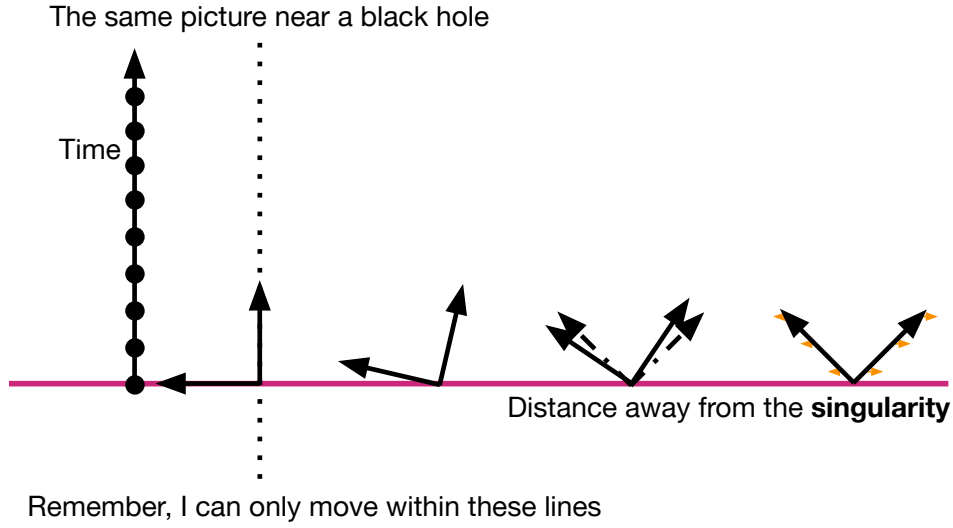


In general relativity, **light** is affected by gravity!

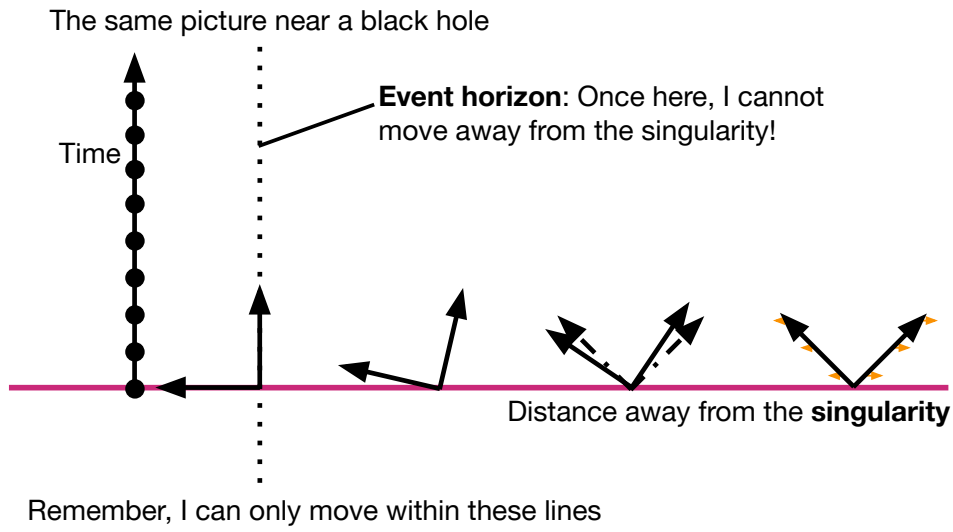
What are black holes?



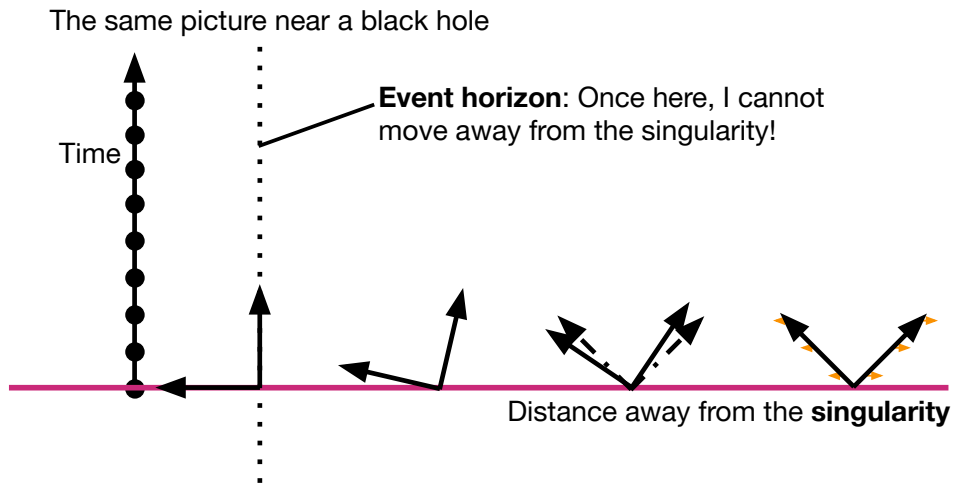
What are black holes?



What are black holes?

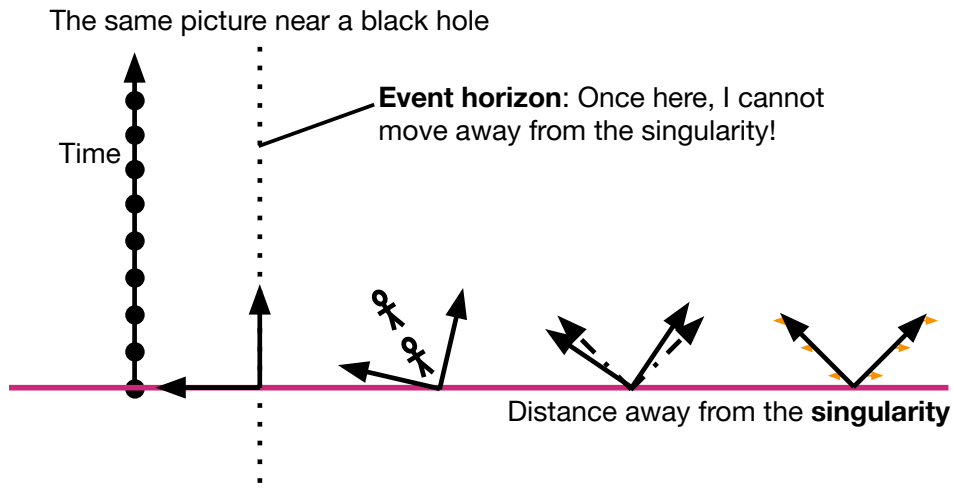


What are black holes?



At some point the cone tips enough that, and because I cannot move outside of it, I am trapped in the sense that I cannot move (along the x-axis) away from the singularity. This point in space where I am trapped is the event horizon.

What are black holes?



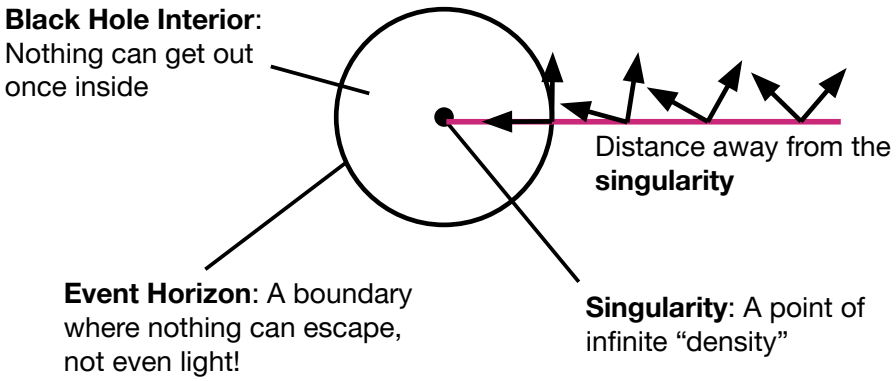
Remember, I can only move within these lines

In fact, in a technical sense, within the event horizon time and space switch places

I think this slide should be skipped.

What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

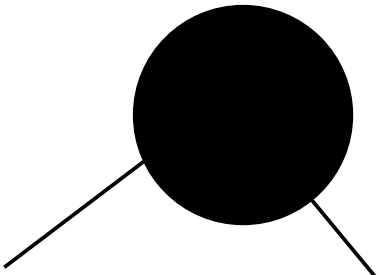


Of course, the previous slides only show what happens when I move closer to the singularity in one particular direction (the x-axis of the previous slide), but in reality the same happens in every direction. This means that the event horizon is a sphere.

What are black holes?

Black hole: A region of such strong gravity that even light cannot escape

In astrophysics we often don't care about what's inside the event horizon, so we draw black holes like this:



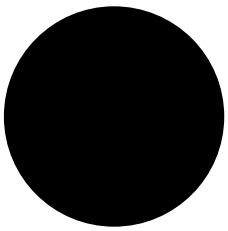
Event Horizon: A boundary where nothing can escape, not even light!

Singularity: hidden inside the event horizon

Part II: How do we take photographs of black holes?

How do we see black holes?

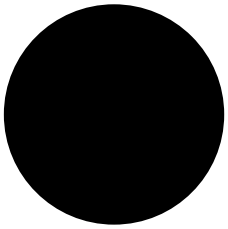
If not even light can escape a black hole, how can we see them?



Slides 56-59 describes that while a black hole itself is invisible, the surrounding “stuff” around it is bright. This bright stuff is what we see when we take pictures of a black hole.

How do we see black holes?

While a black hole is invisible, the region around it is **bright**



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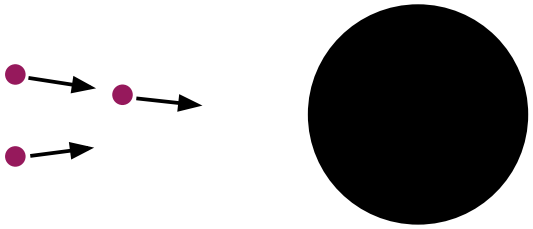

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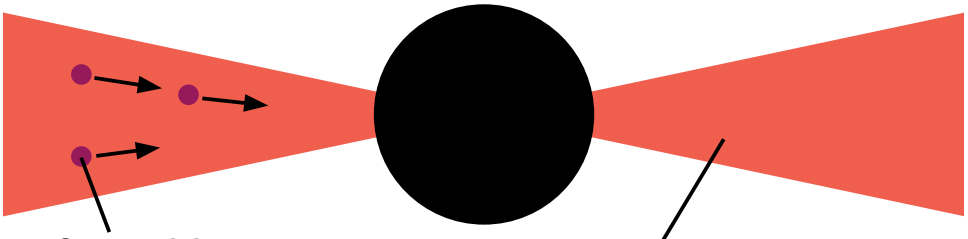
While a black hole is invisible, the region around it is **bright**

-) Gas particles **speed up** as they get sucked into the black hole
-) **Friction** heats falling material, turning them into **bright**, **hot plasma**



Gas particles: the accretion disk is composed of particles falling into the BH

Accretion disk: hot, bright plasma, what telescopes actually “sees”

Part III: Black holes as laboratories of strong gravity

I suggest skipping Section III in favor of spending more time on the first two sections.

Part III: Black holes as laboratories of strong gravity

Let's check whether Einstein was right

Black Holes as Laboratories of Strong Gravity

Is **Einstein's theory of gravity (general relativity)** correct?

We can model black holes using general relativity

Black Holes as Laboratories of Strong Gravity

Is **Einstein's theory of gravity (general relativity)** correct?

We can model black holes using general relativity

How do we know whether this is really the right model?

How do we know whether black holes in space are Einstein's black hole?

Black Holes as Laboratories of Strong Gravity

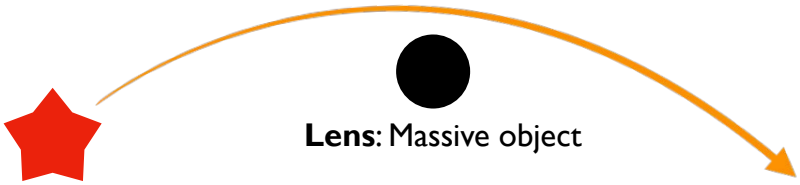
Can we devise astrophysical observations to test which of these are true?

Einstein's black hole: A black hole as we know it

?!?!?

Black Holes as Laboratories of Strong Gravity

Gravitational lensing



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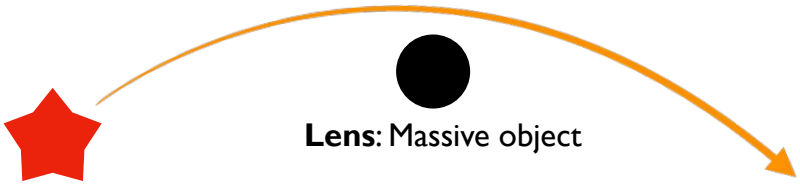

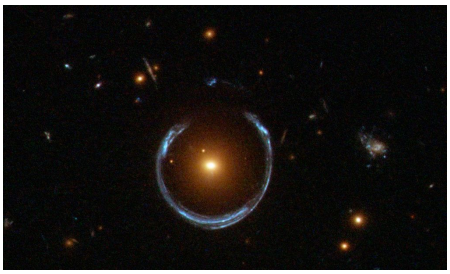

Images credit: NASA/Stsci - Hubble Space Telescope

Black Holes as Laboratories of Strong Gravity

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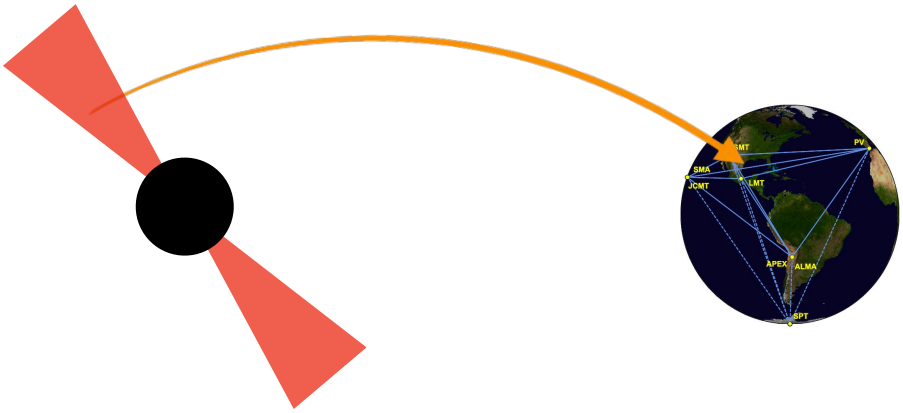

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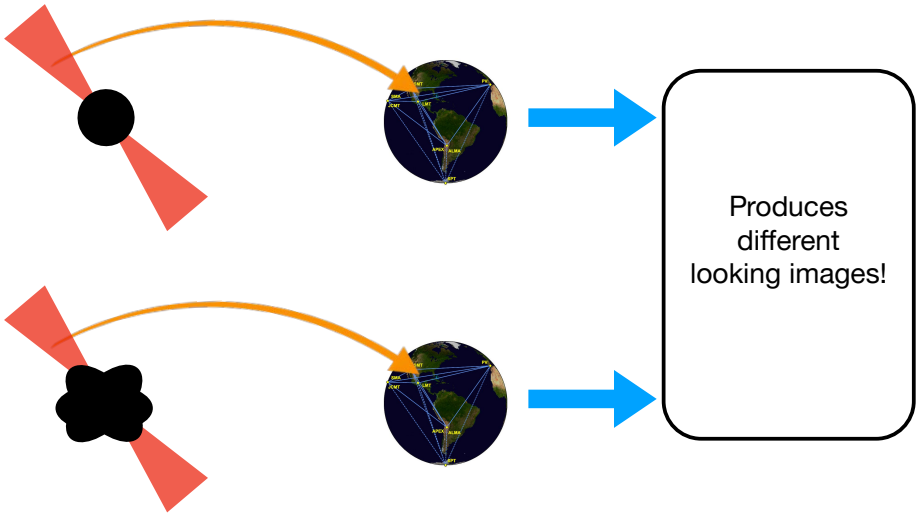

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Speaker Notes for Black Hole Orbits

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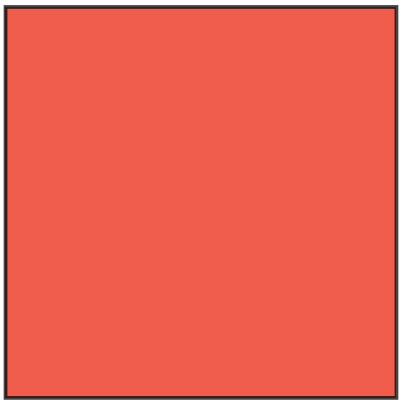

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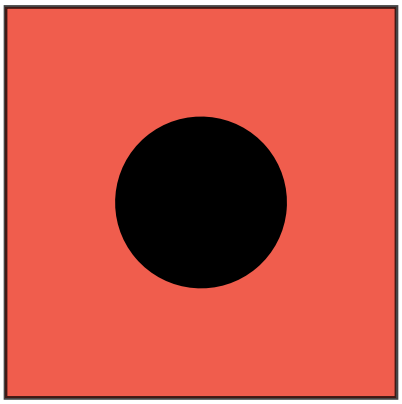

Images credit: Hotaka Shiokawa

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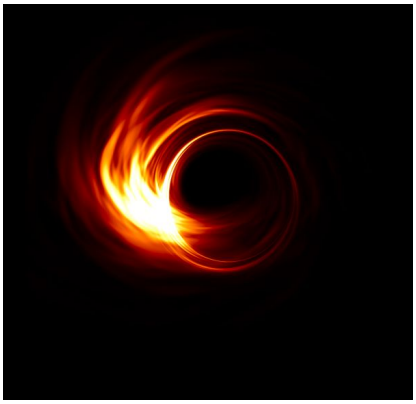

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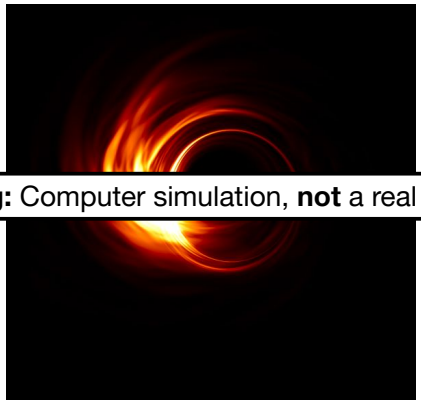

Warning: Computer simulation, **not** a real black hole!

Image credit: EHT Collaboration, Hotaka Shiokawa

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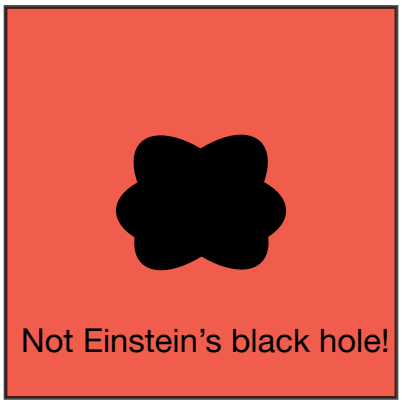

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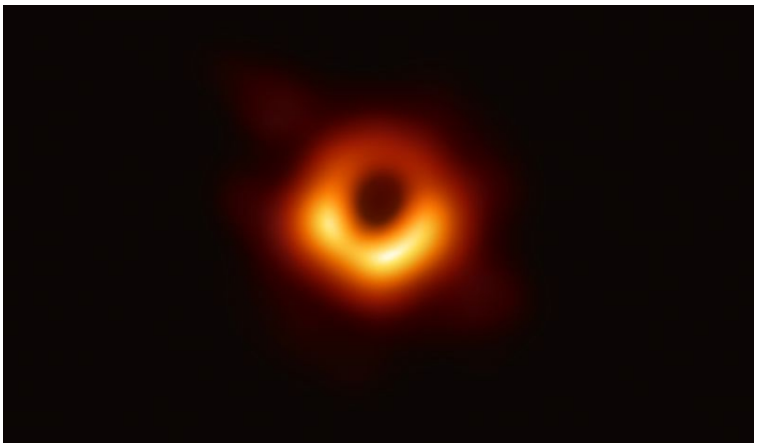

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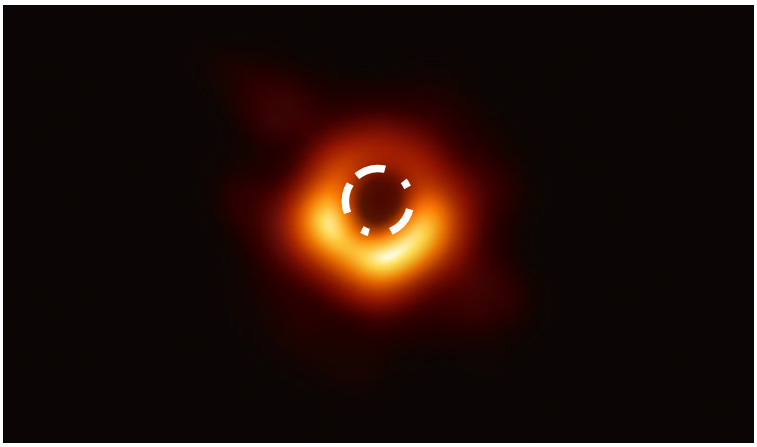

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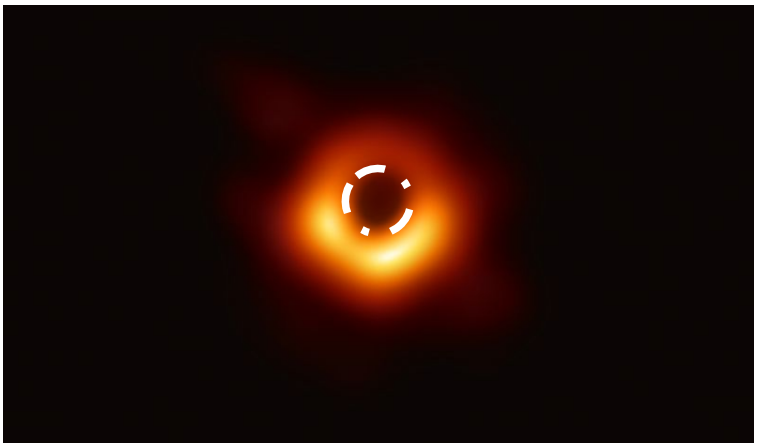

So far, Einstein is **vindicated**!

Thank you!

How do we see black holes?

Another problem: black holes are very small and very far away!

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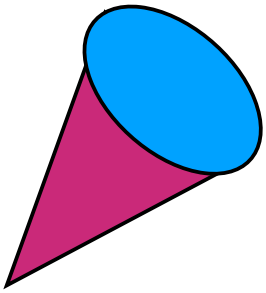
M87's BH: 50 million light-years away, ~10s of microarcseconds diameter

How do we see black holes?

Can I resolve something with my telescope?



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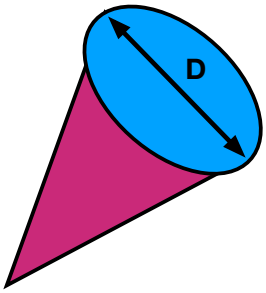
The **larger** the telescope, the **larger** the resolution!



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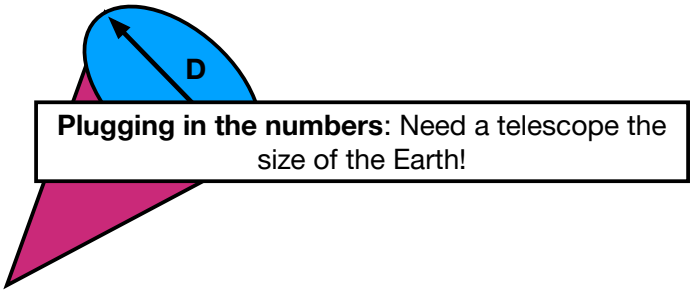

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Image credit: SMT, SPT

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Arizona **L** **South Pole**

Image credit: SMT, SPT

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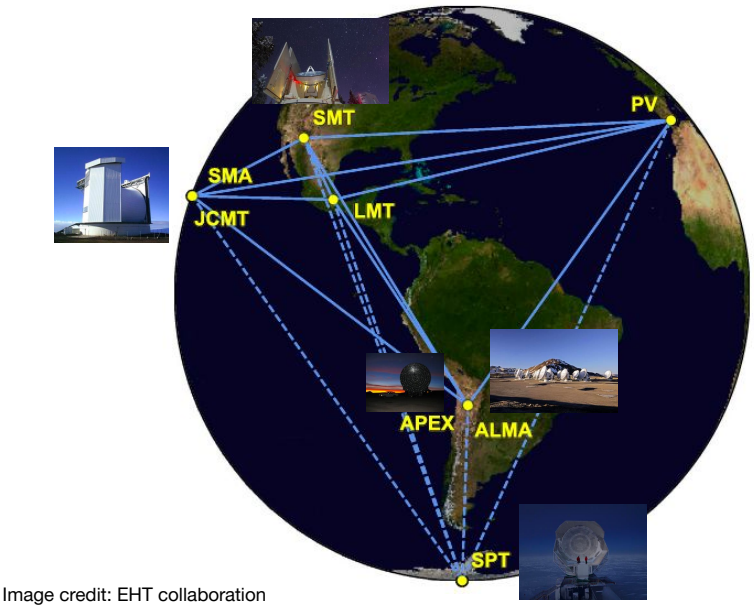

Image credit: EHT collaboration

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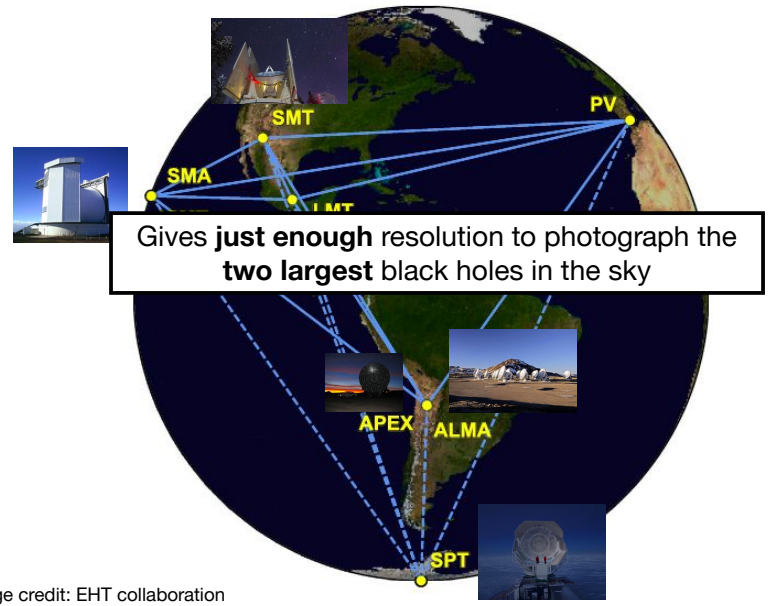

Gives **just enough** resolution to photograph the **two largest** black holes in the sky

Image credit: EHT collaboration

Black Holes as Laboratories of Strong Gravity

Why is this important?

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1) There is no closed timelike loop (no time travel)

2) Nature abhors singularities without event horizons

Black Holes as Laboratories of Strong Gravity

Why is this important?

The **Kerr-Newman** black hole is not derived just using general relativity

In addition it requires the following to be true:

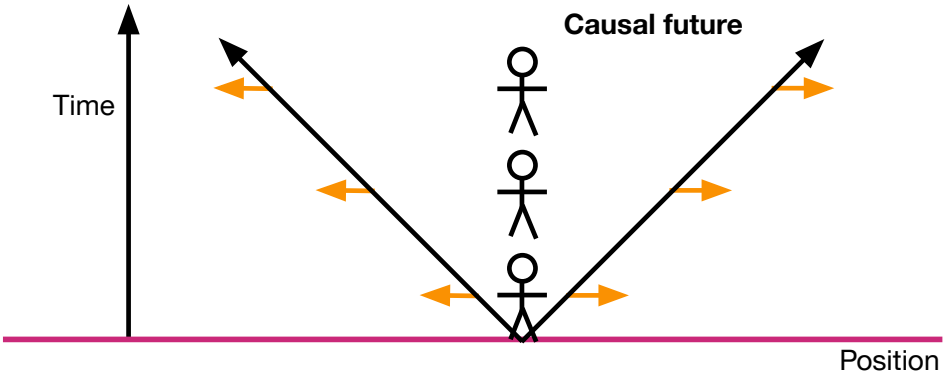
1) There is no closed timelike loop (no time travel)

2) Nature abhors singularities without event horizons

Testing whether **Kerr-Newman** black holes are real is not only a test of relativity, but also of these basic philosophical principles

Black Holes as Laboratories of Strong Gravity

1) There is no closed timelike loop (no time travel)



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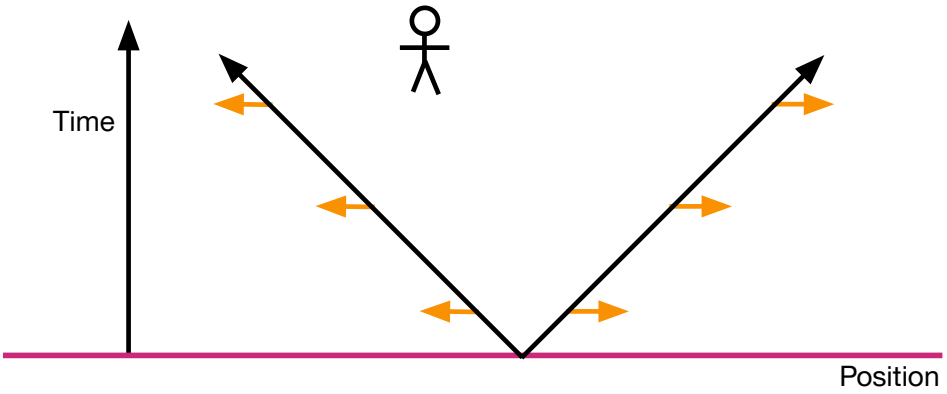

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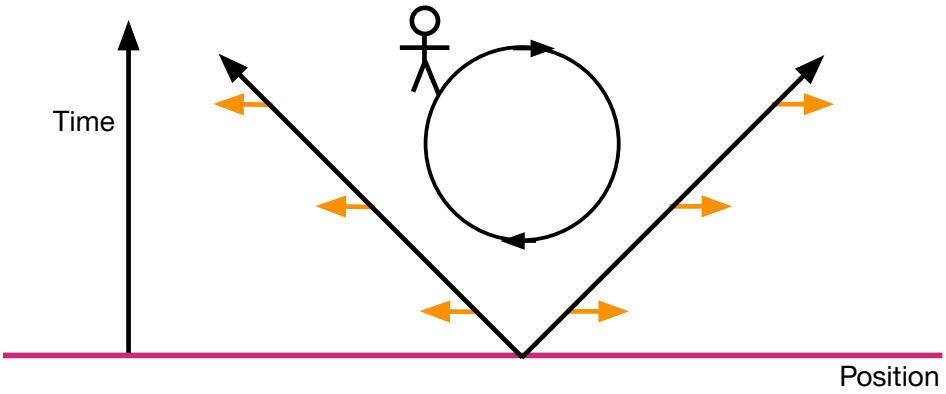

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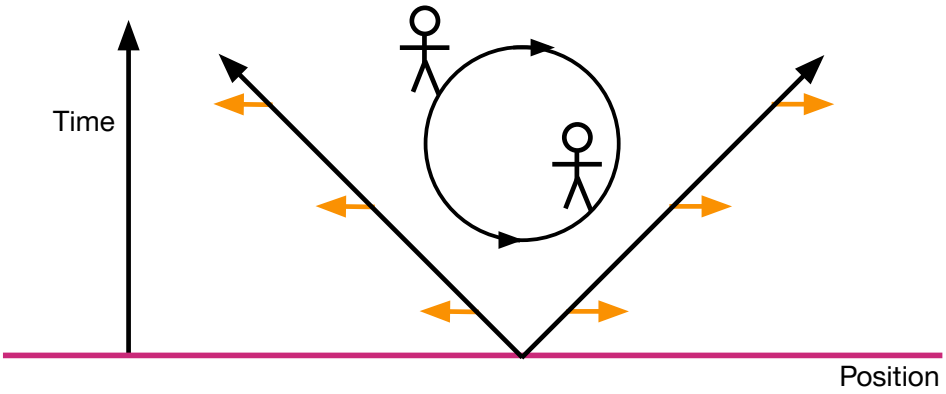
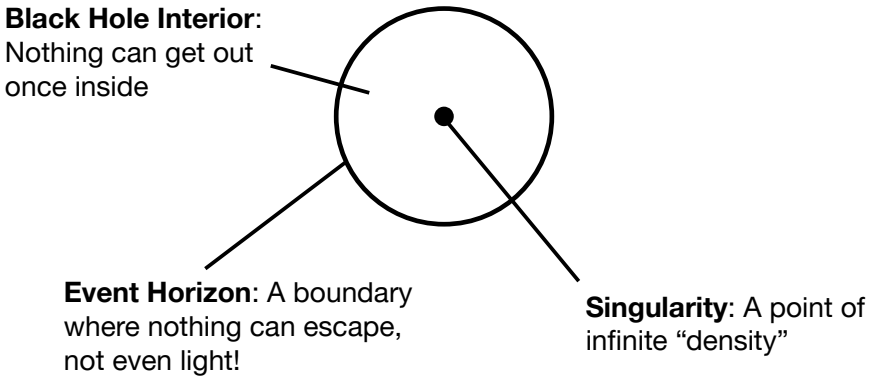


Black Holes as Laboratories of Strong Gravity

2) Nature abhors singularities without event horizons



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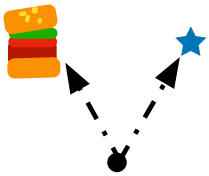

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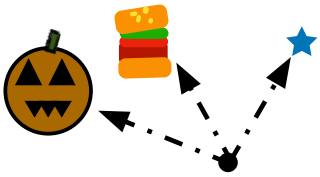

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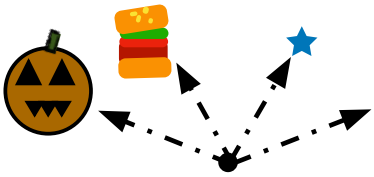

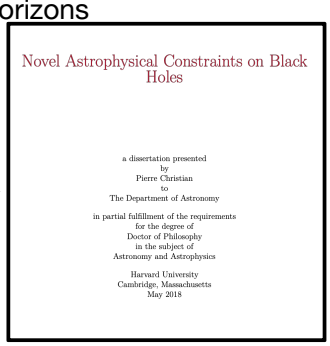

Novel Astrophysical Constraints on Black Holes

a dissertation presented
by
Pierre Christian
to
The Department of Astronomy

in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy
in the subject of
Astronomy and Astrophysics

Harvard University
Cambridge, Massachusetts
May 2018

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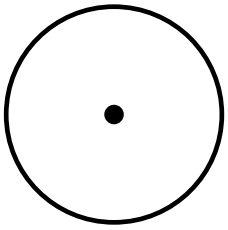

Singularities are **bad**, because there physics as we know it breaks down

However, if it is **hidden** in a horizon, it is *more* okay, because nothing can escape the event horizon, so the *badness* is **imprisoned** and not allowed to spoil the rest of the Universe.

A little bit about myself

Theoretical astrophysics:

Studying the Universe through applying principles of physics

A little bit about myself

Theoretical astrophysics:

Studying the Universe through applying principles of physics

Contrast with Observational astrophysics:

Studying the Universe by observing it, usually through a telescope

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Theoretical astrophysics research is done "in your head" with pen and paper, or with a computer

Example theoretical astrophysics questions:
What happens to a person close to a black hole?
What is inside a black hole?
What happens at the end of time?

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Speaker Notes for Black Hole Orbits

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You might enjoy theoretical astrophysics if you enjoy:

-) Solving math problems
-) Computer programming
-) Abstract thinking
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Majors to consider in college for theoretical astrophysics:

-) Physics
-) Astronomy
-) Mathematics
-) Computer science
-) Statistics