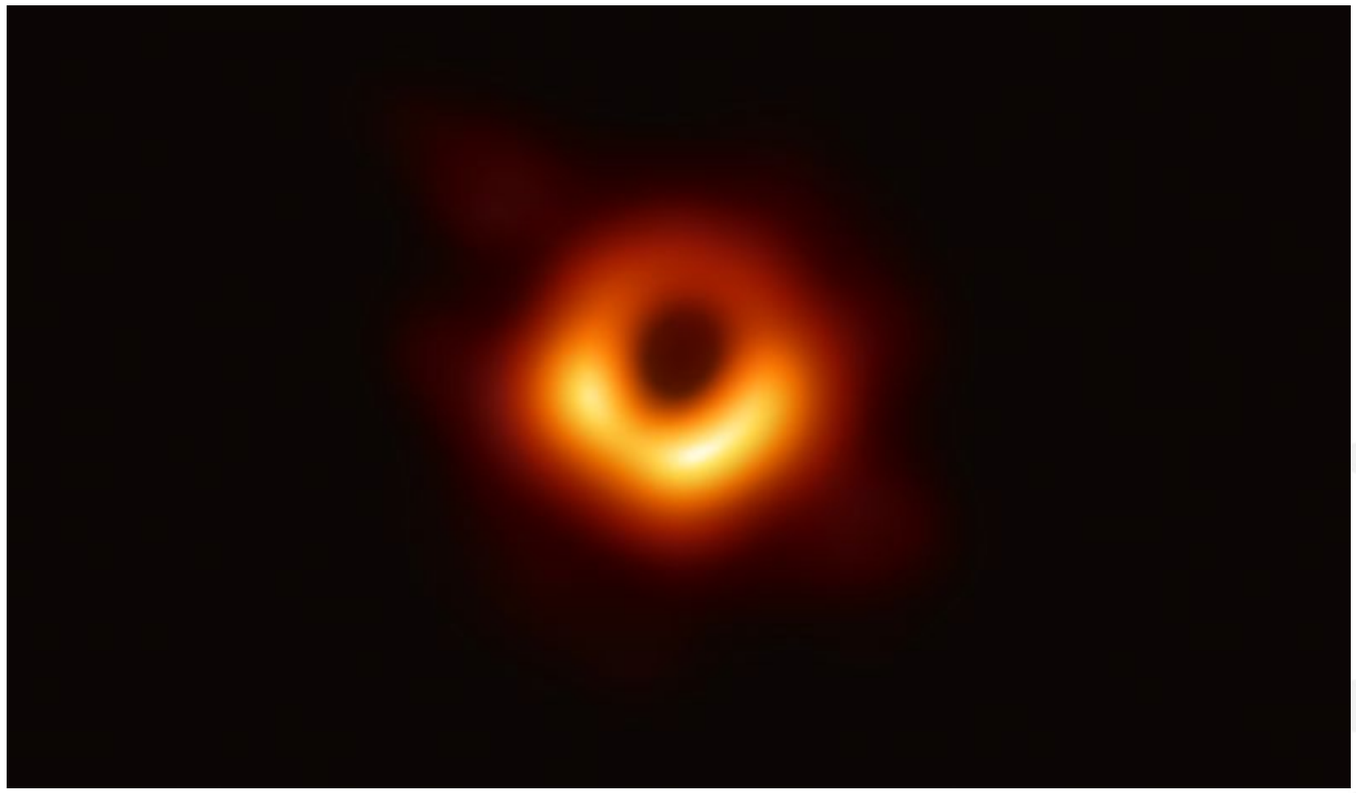
# TEEN ASTRONOMY *Café* – To Go!



Pierre Christian

# Testing Einstein’s Gravity with Black Holes

Teen Astronomy Cafe Oct 2019

# A little bit about myself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Images credit: The Jakarta Post

# A little bit about myself

## Why did I choose to be an astrophysicist?

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The most interesting things are in space!

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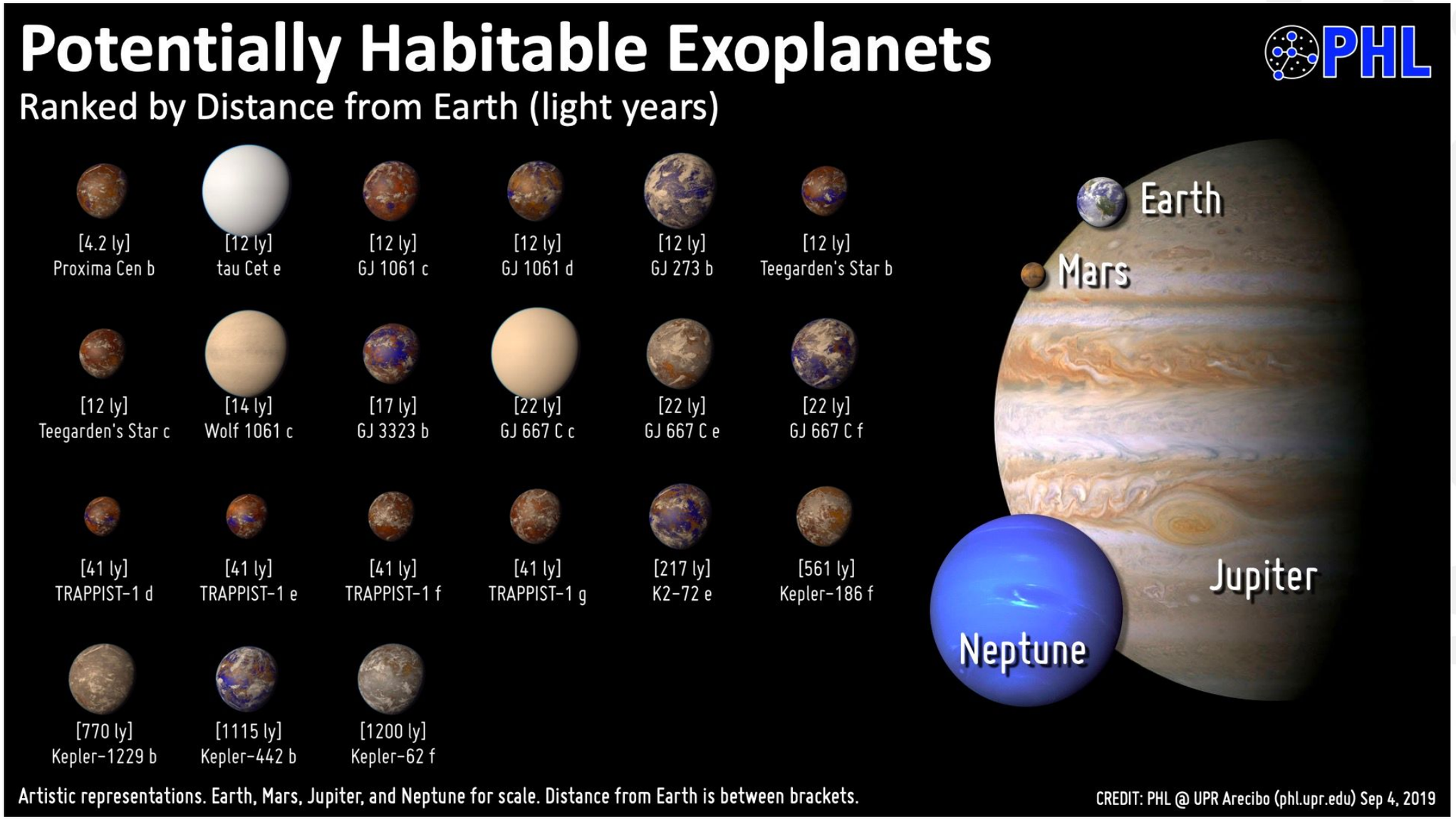


**Exoplanets:** Alien worlds outside our solar system

Image credit: Planetary Habitability Laboratory, University of Puerto Rico

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**Galaxies:** Conglomeration of many billions of stars

Image credit: Robert Gendler

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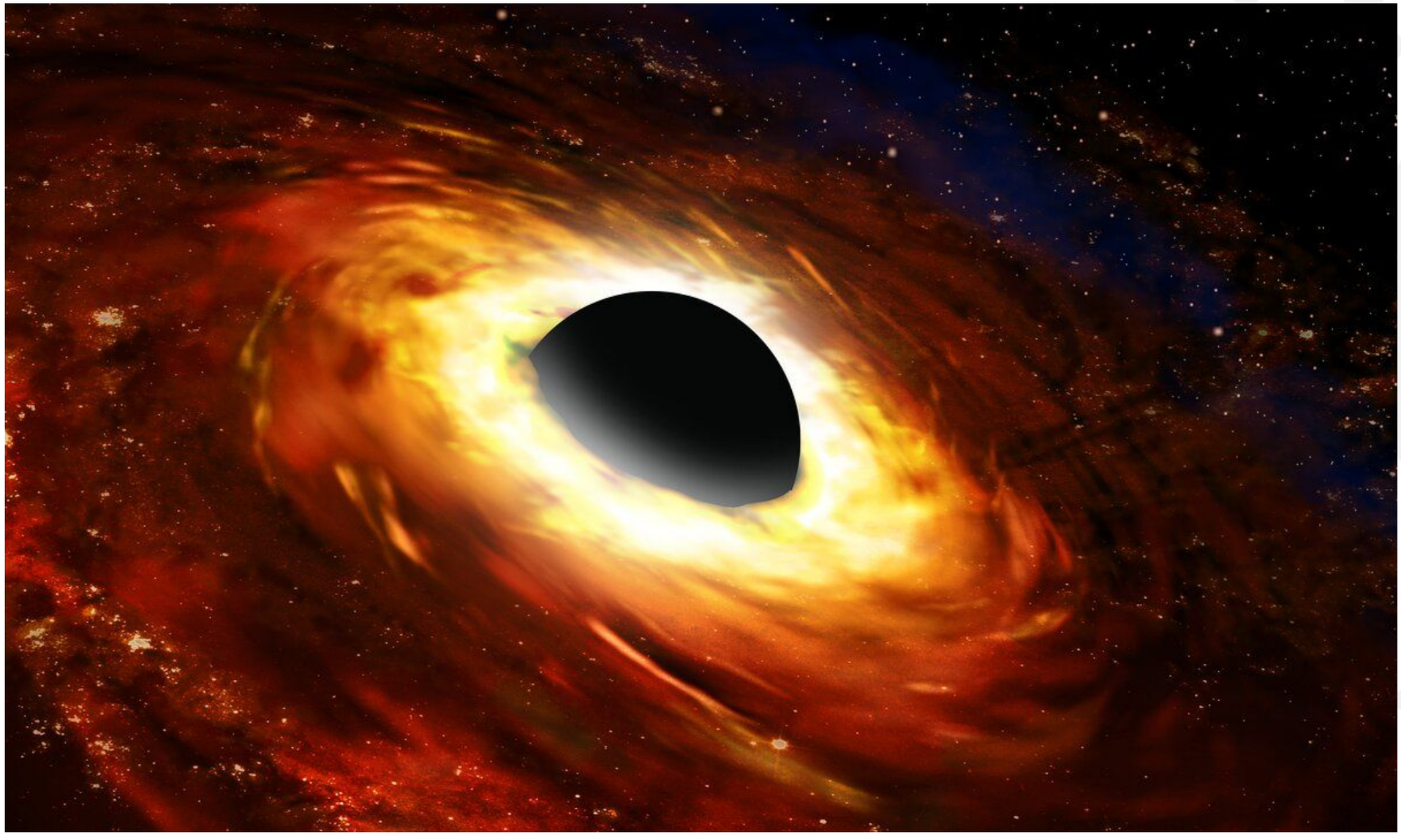

Black Holes

Image credit: NOIRLab/AURA/NSF/P. Marenfeld

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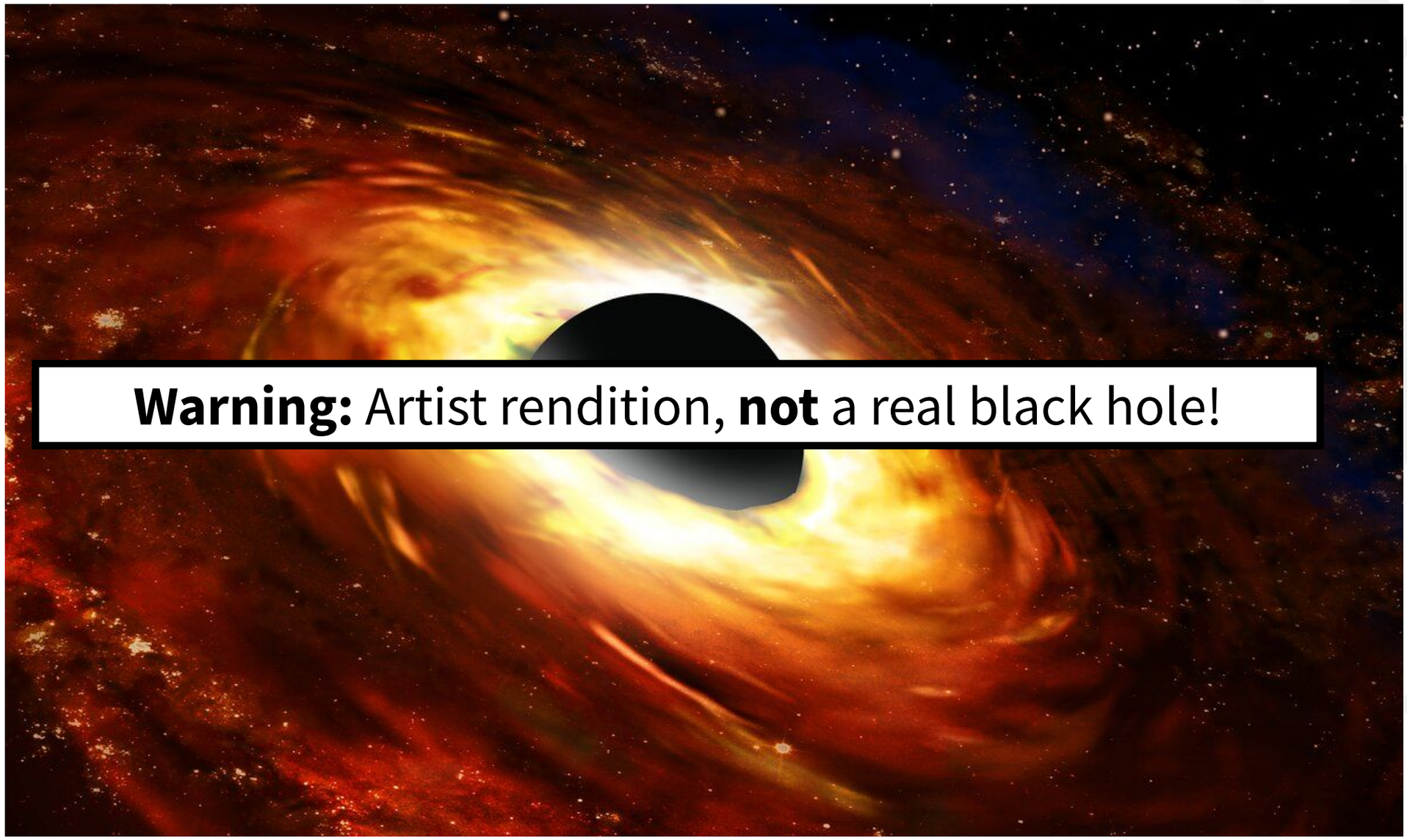


**Black Holes**

# Part I: What are black holes?

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Proposed by Albert Einstein (1879-1955)

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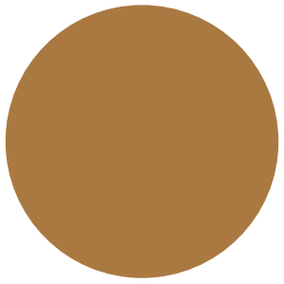

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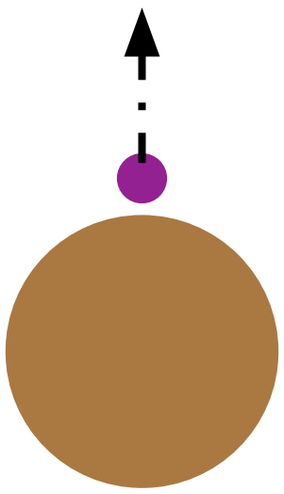

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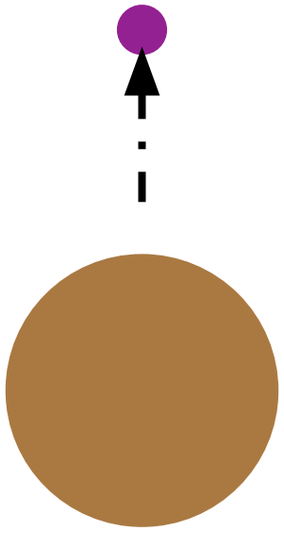

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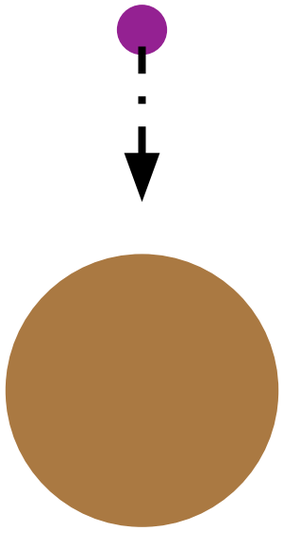

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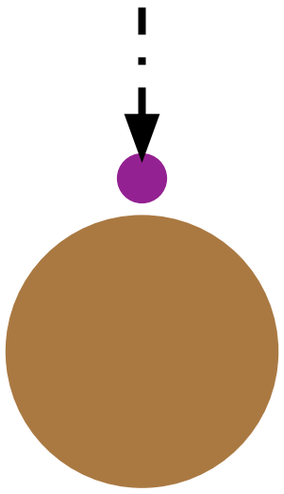

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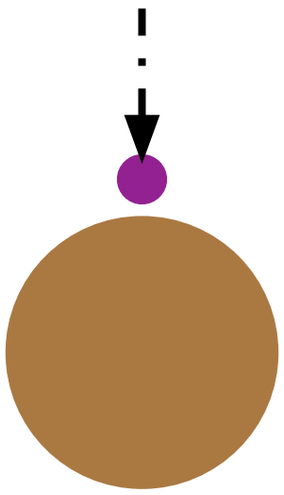
**Question**: If light is affected by gravity, can there be objects where light also falls back down due to gravity?



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

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

Image credit: NASA

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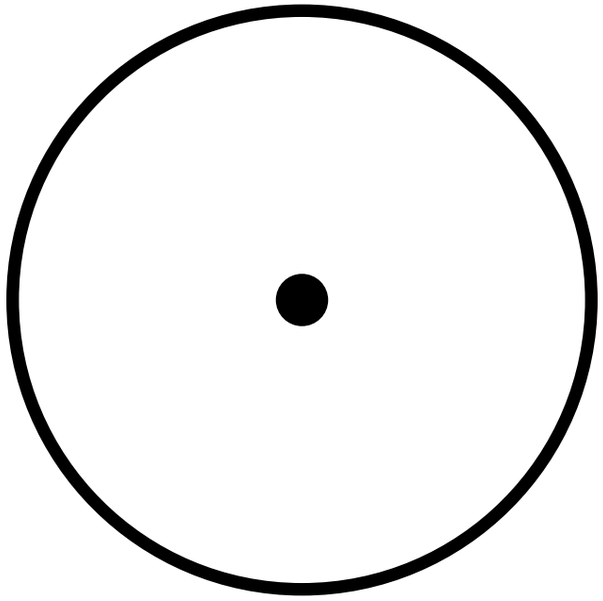

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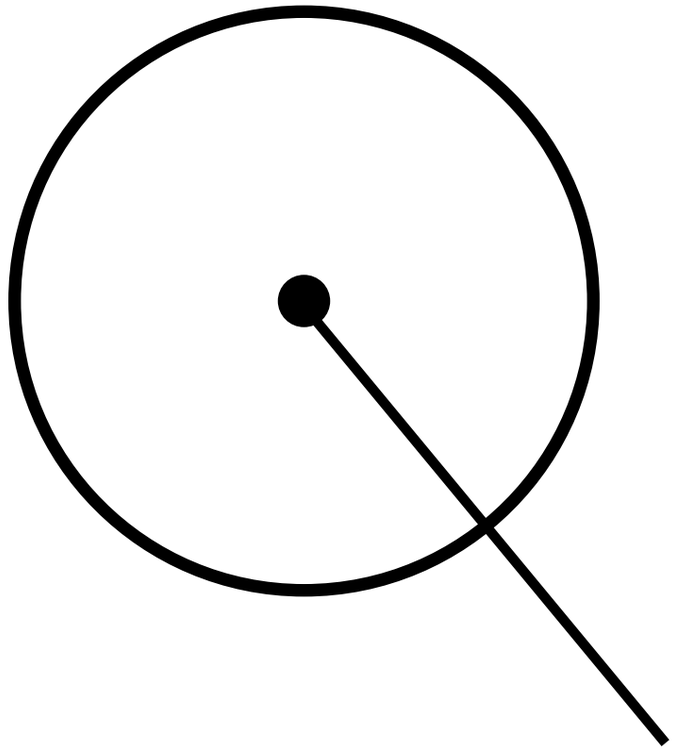

**Singularity**: A point of infinite “density”

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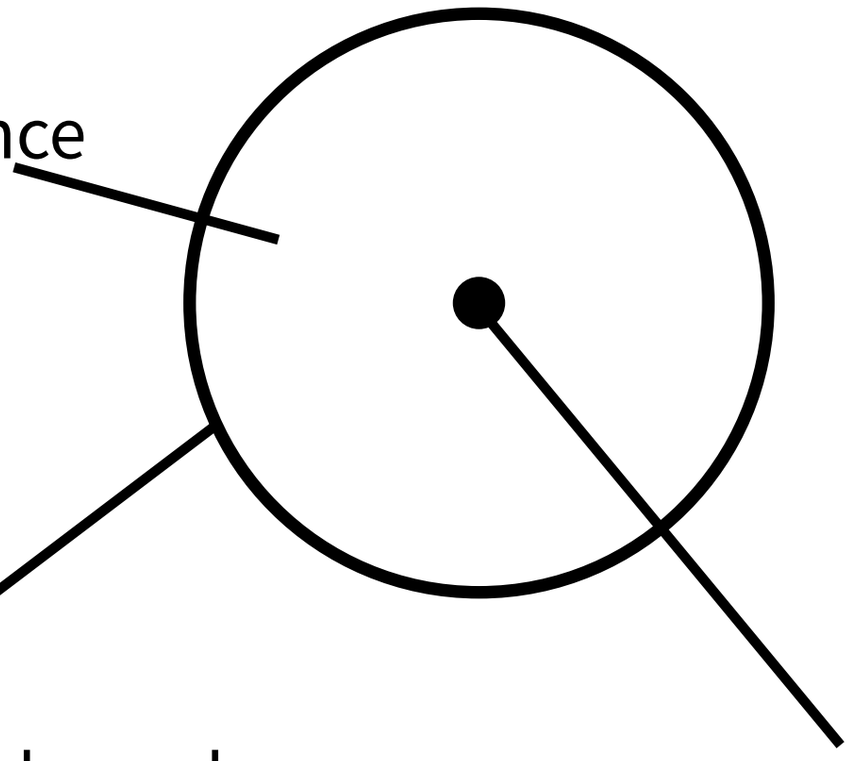

**Event Horizon**: A boundary where nothing can escape, not even light!

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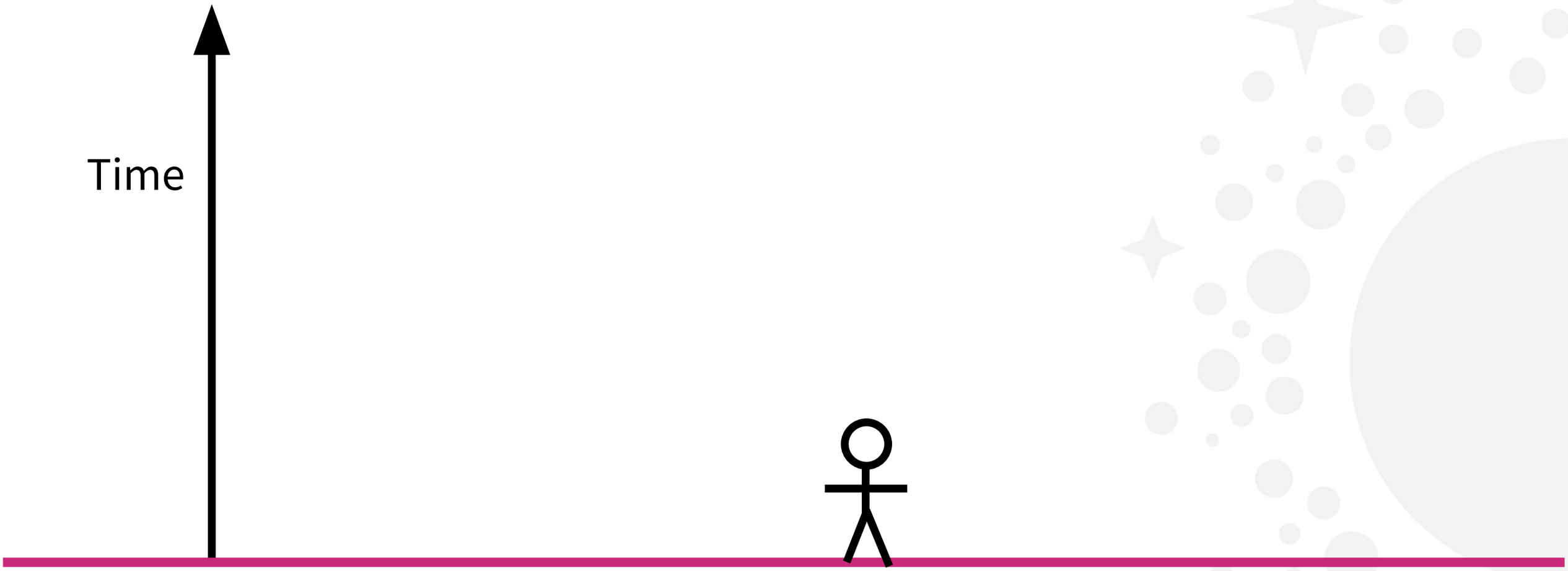
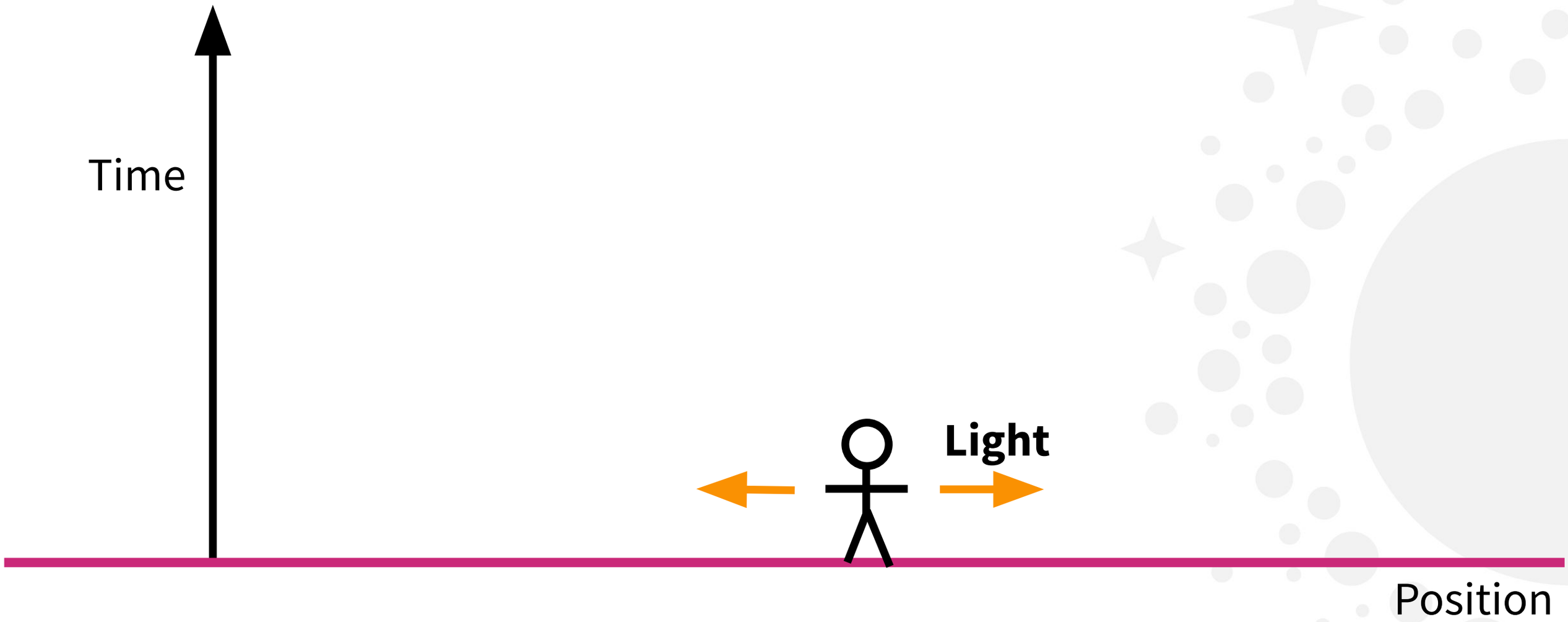



To get a better understanding of black holes, consider the following picture

# 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!

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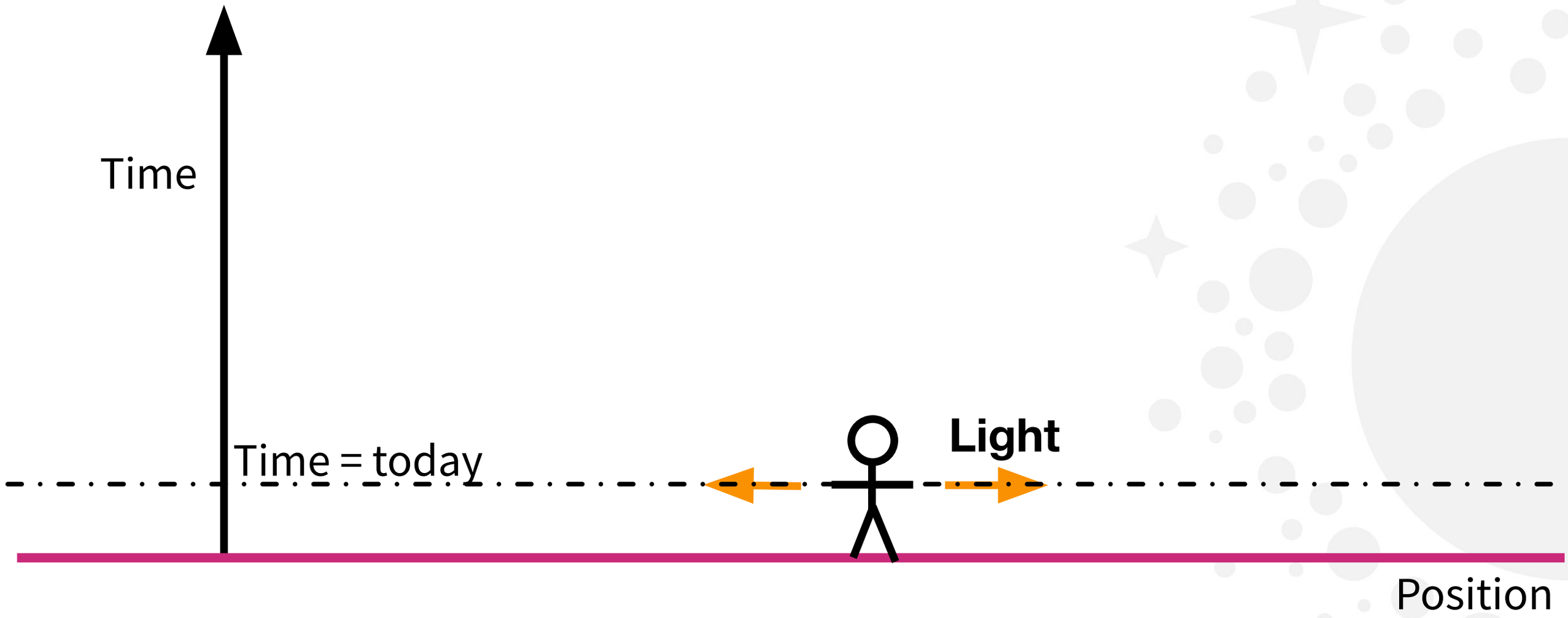


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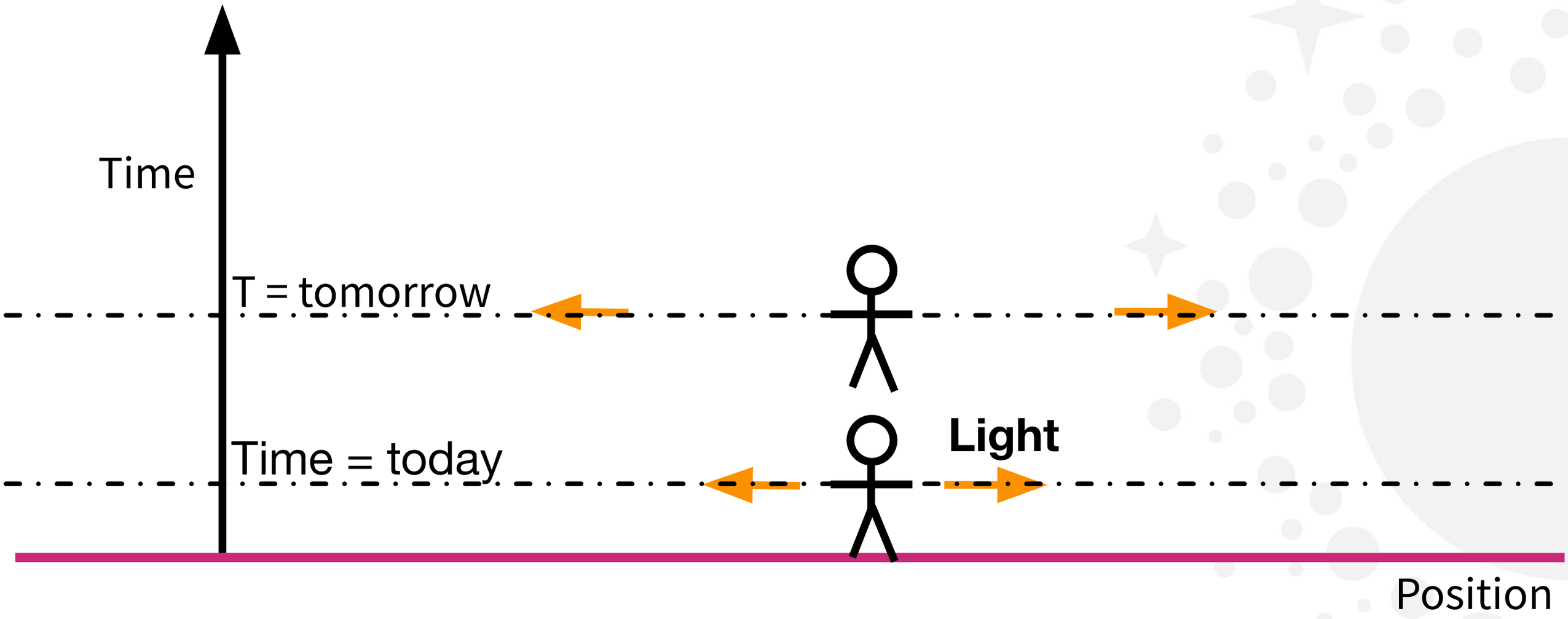


The light beams travel away from me at the speed of light

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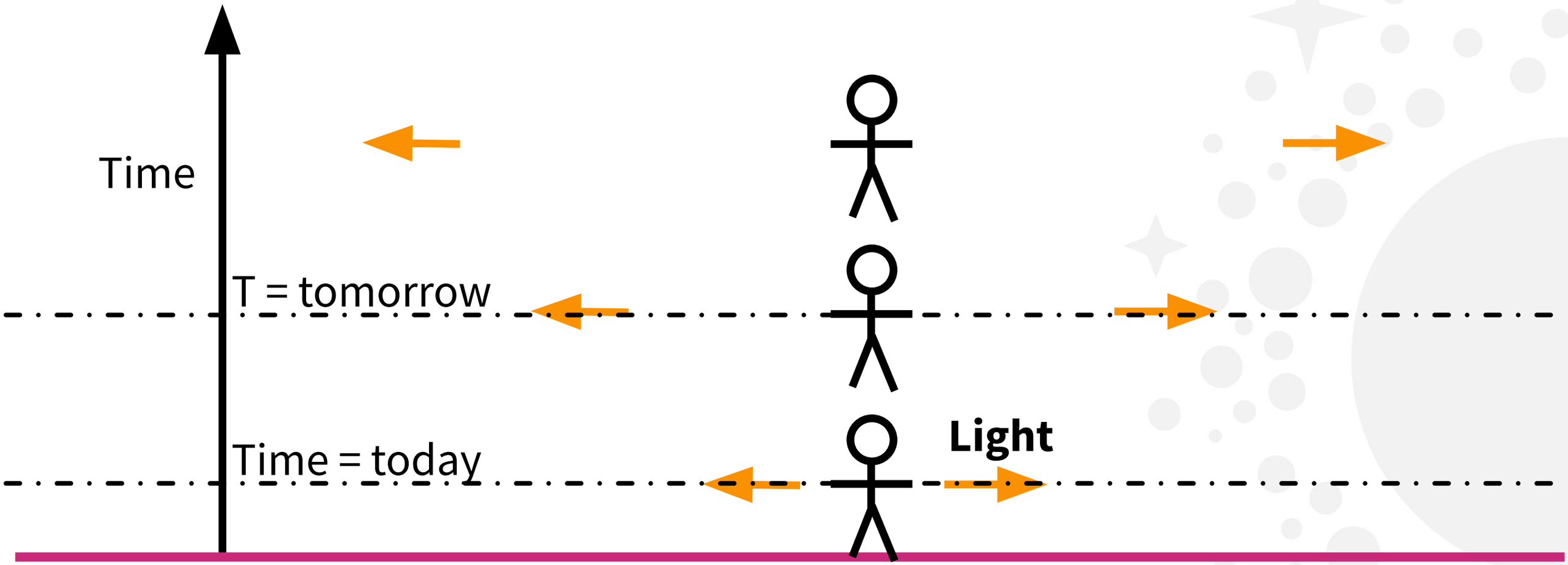


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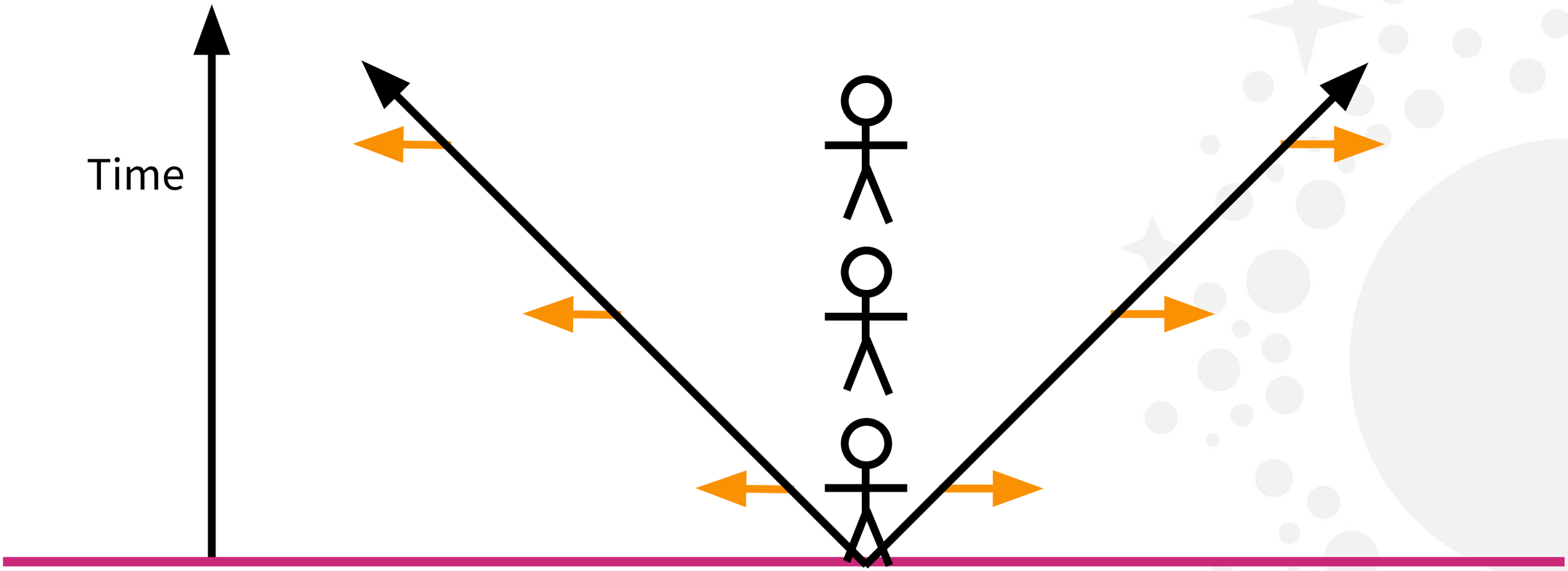

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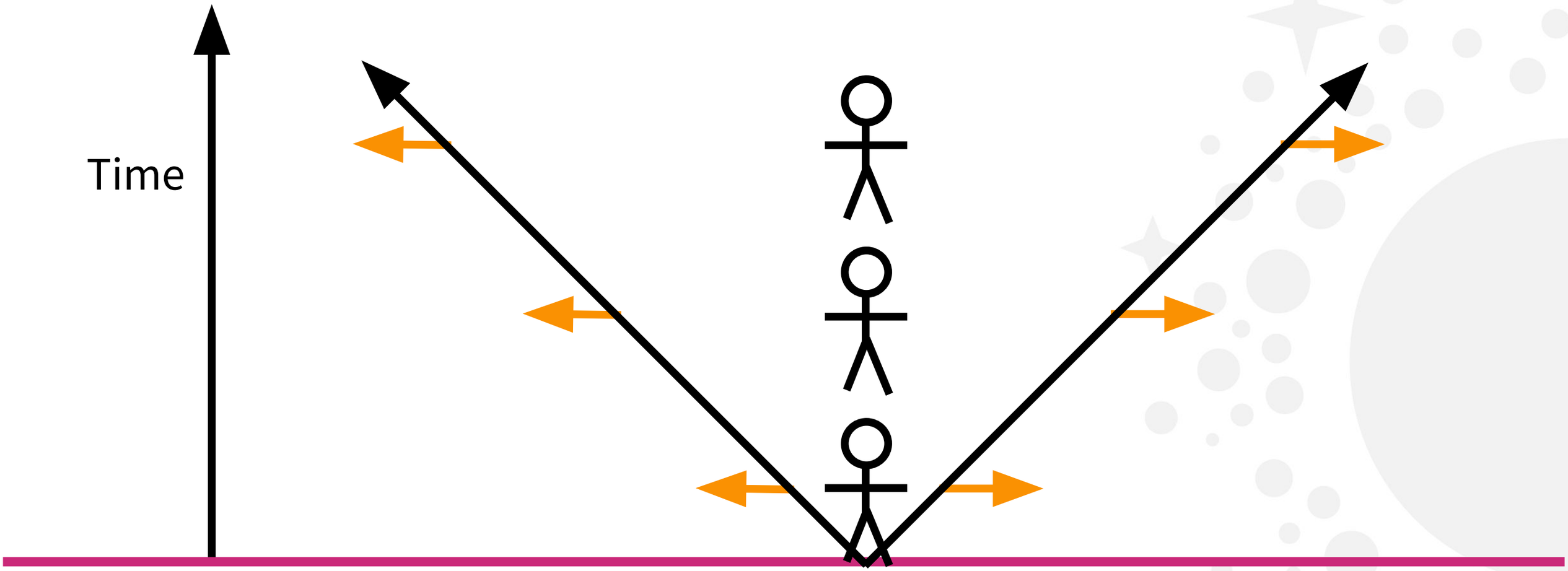


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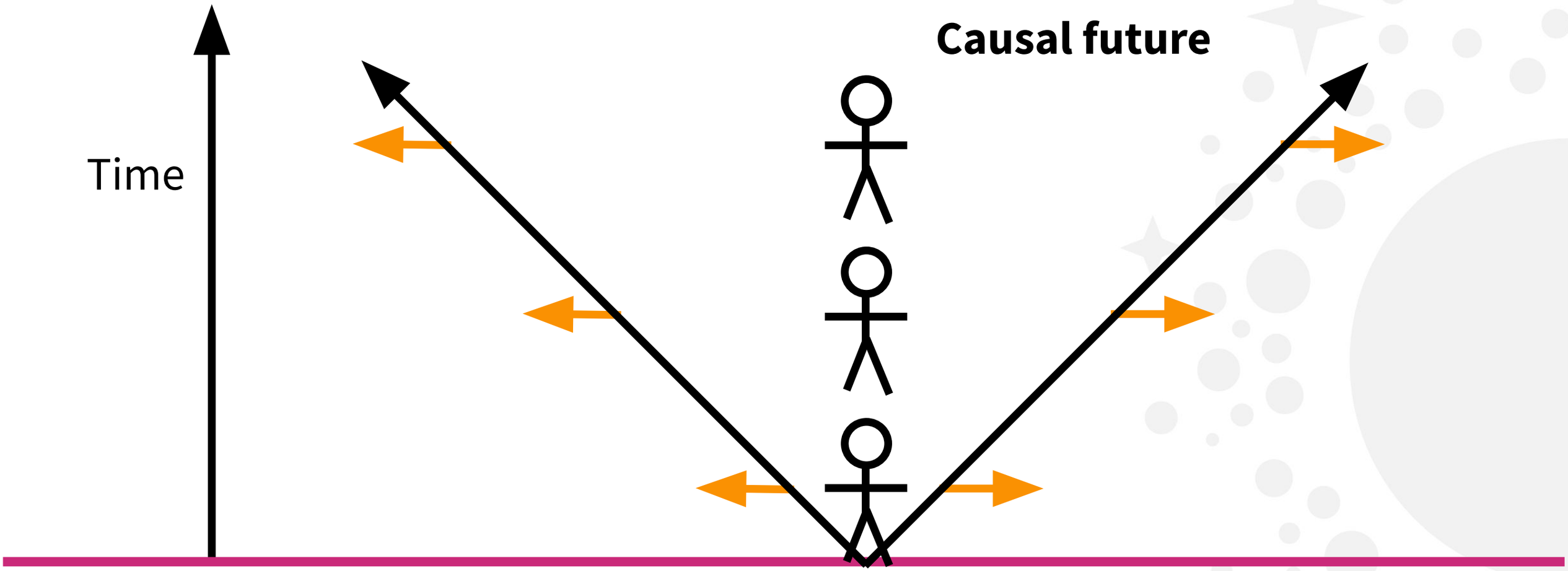


Nothing can travel faster than light (postulate of relativity)

-) I can only move within these lines

-) Everything that I can affect is within these lines (**causal cone**)

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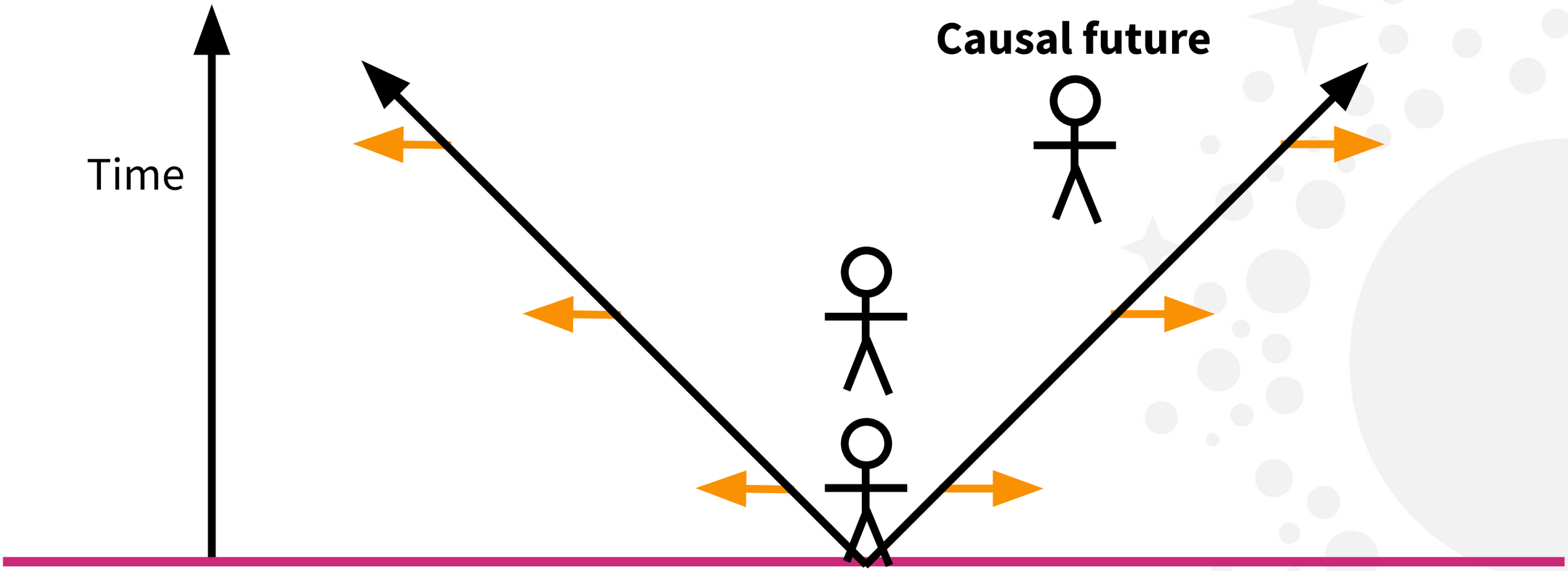


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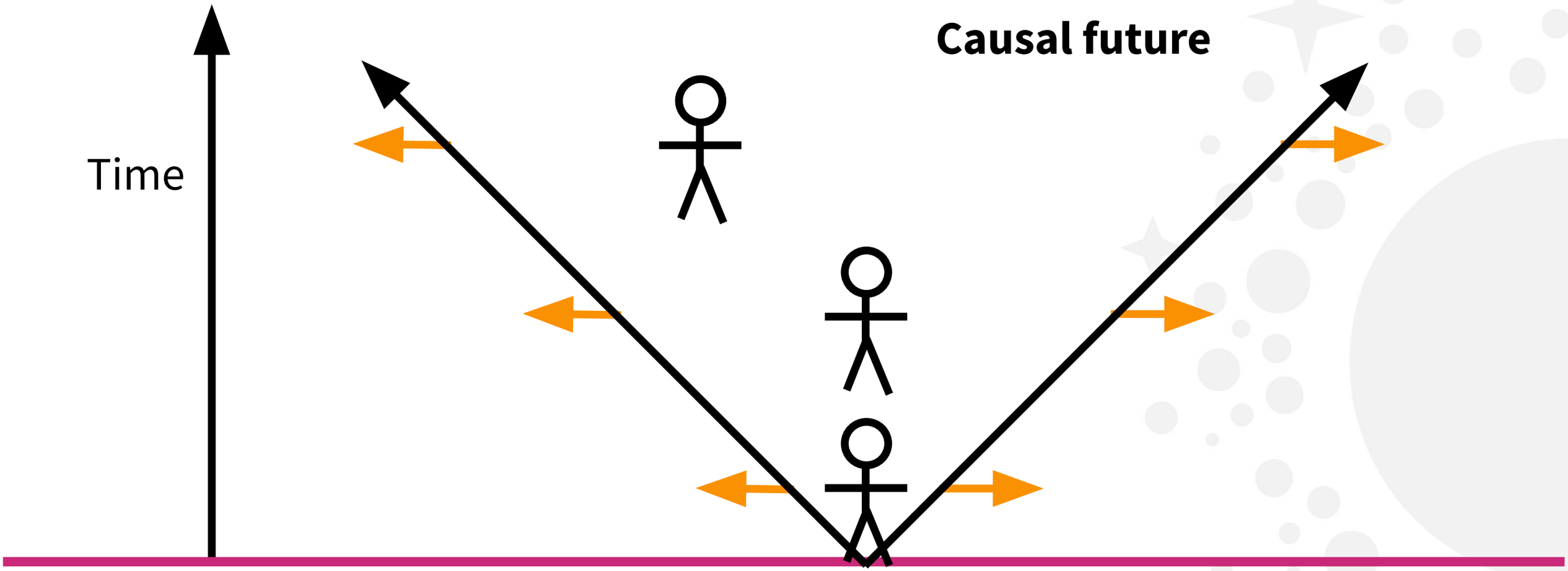


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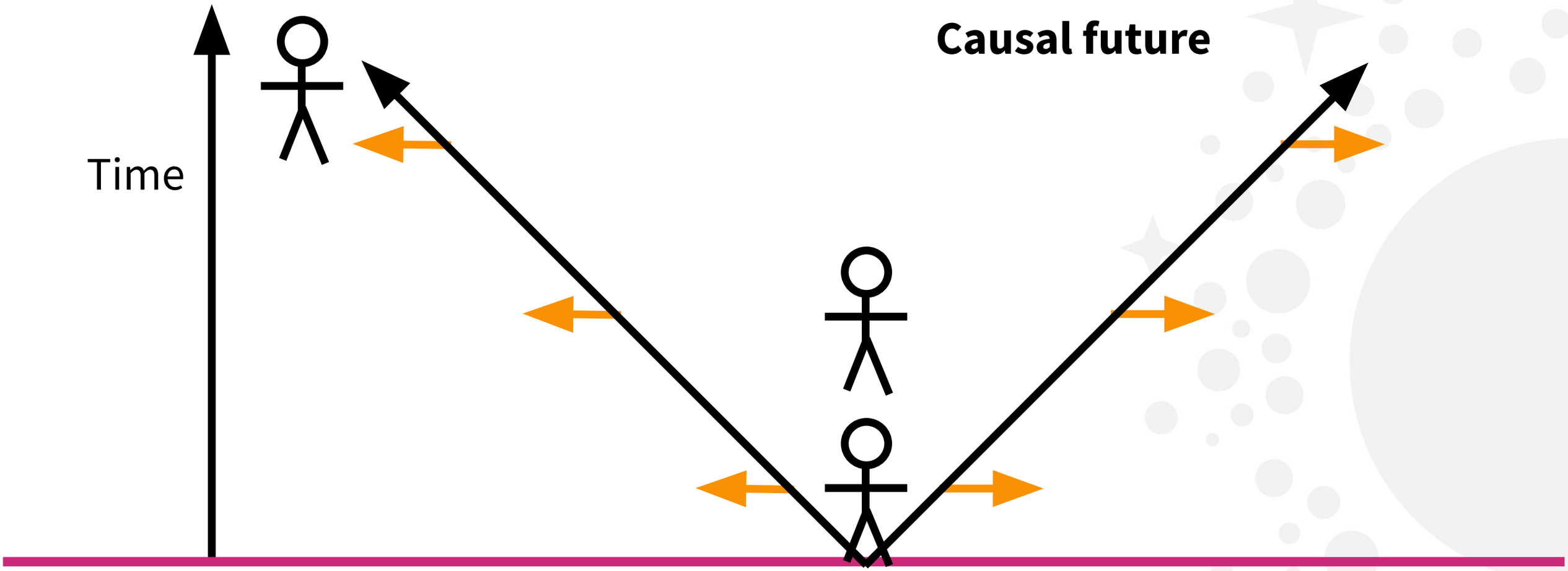


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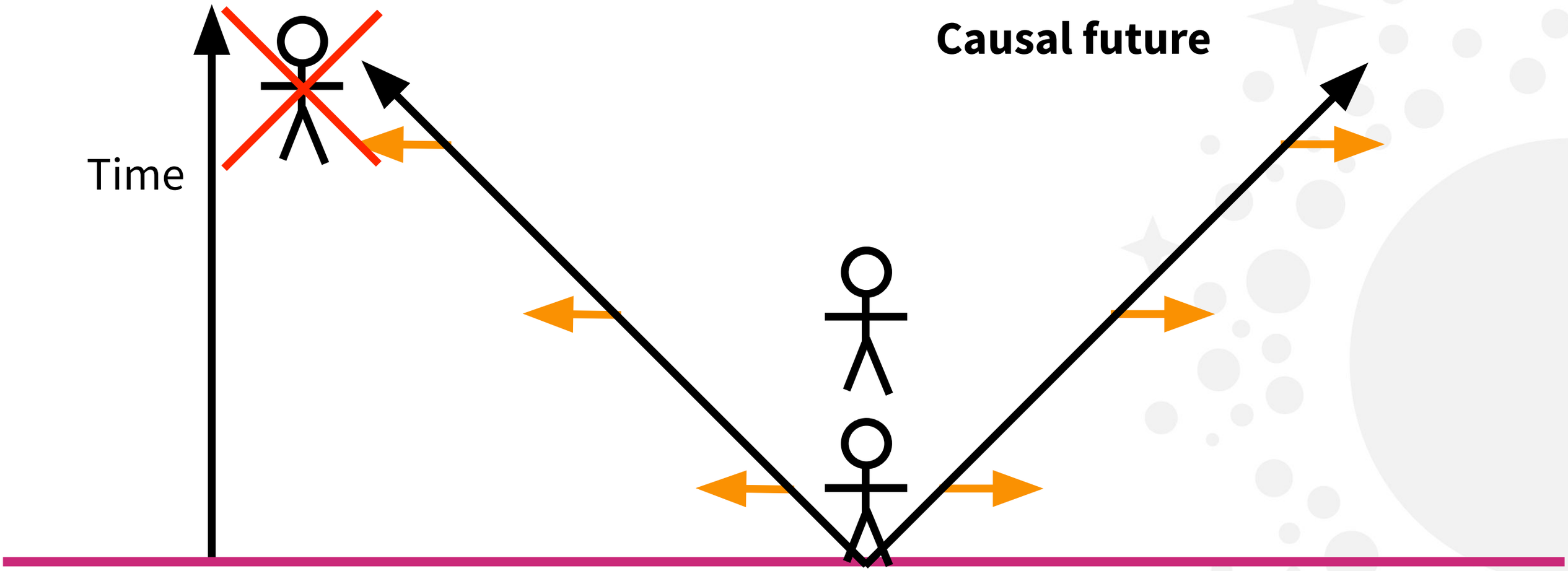


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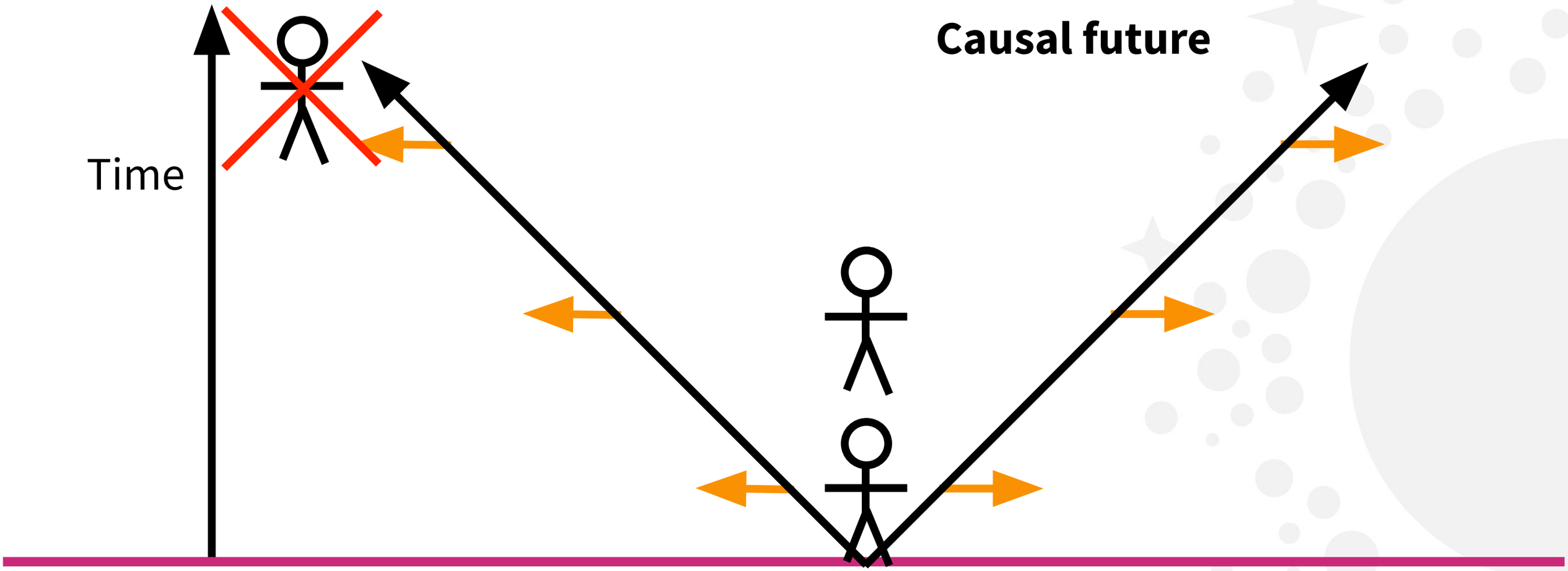


Remember, there is **no** black hole yet in this picture! I am trapped Inside these lines not because there is a black hole, but because I cannot move faster than light!

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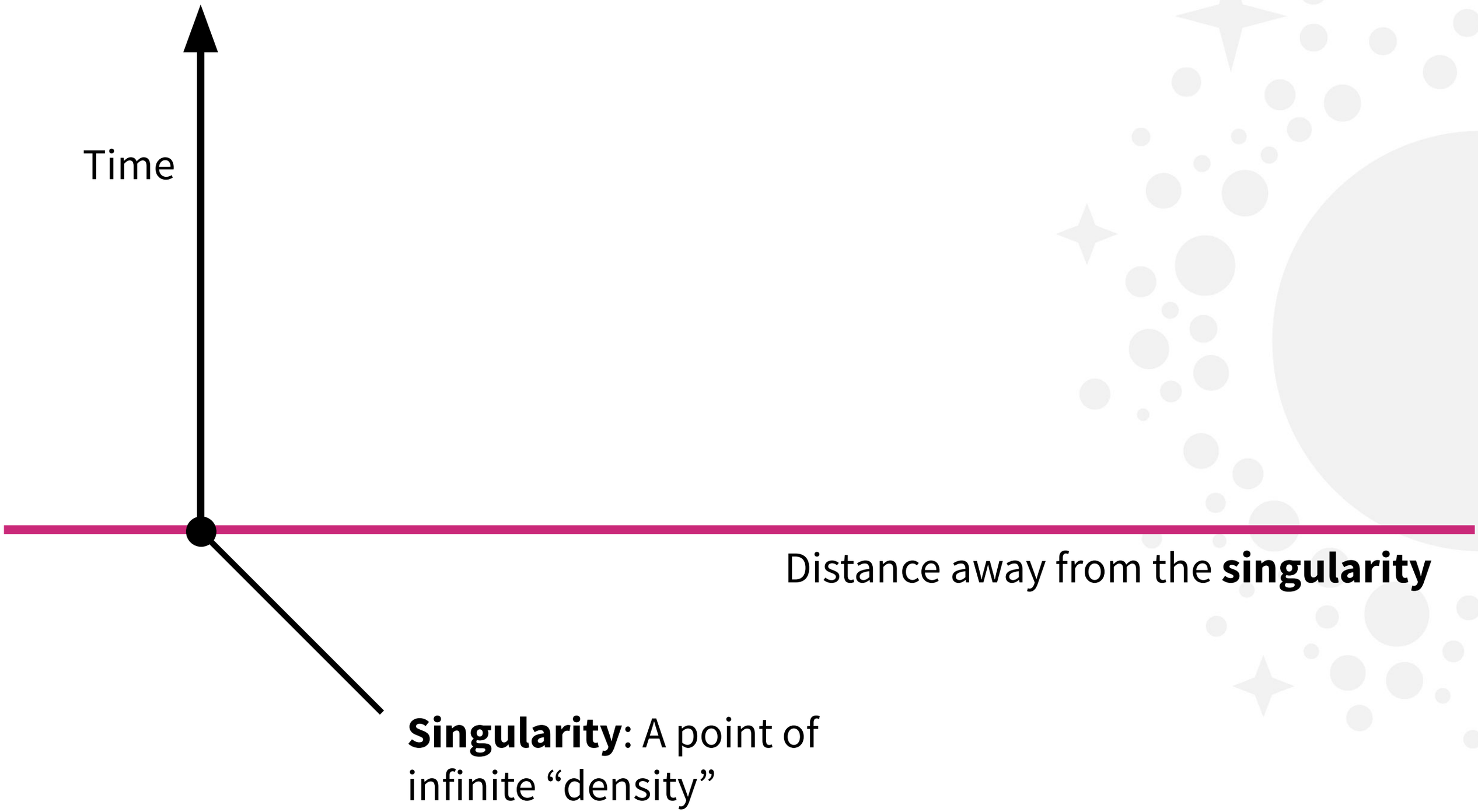
# What are black holes?

The same picture near a black hole

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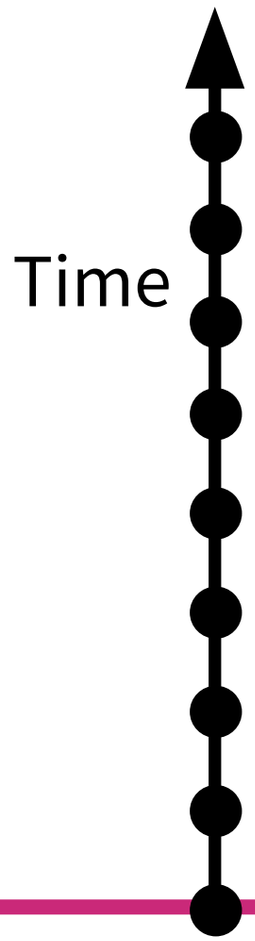
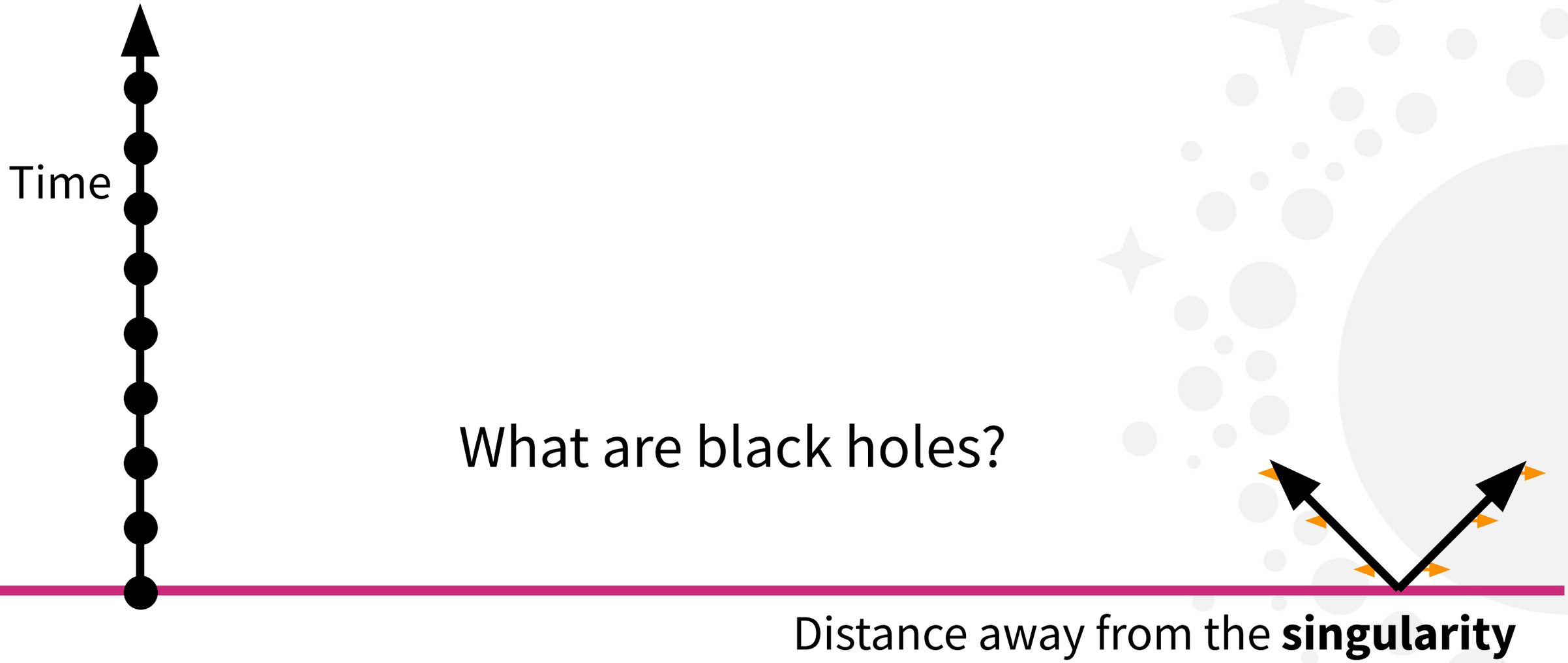



The singularity does not move, so it just goes up in time

The same picture near a black hole




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

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

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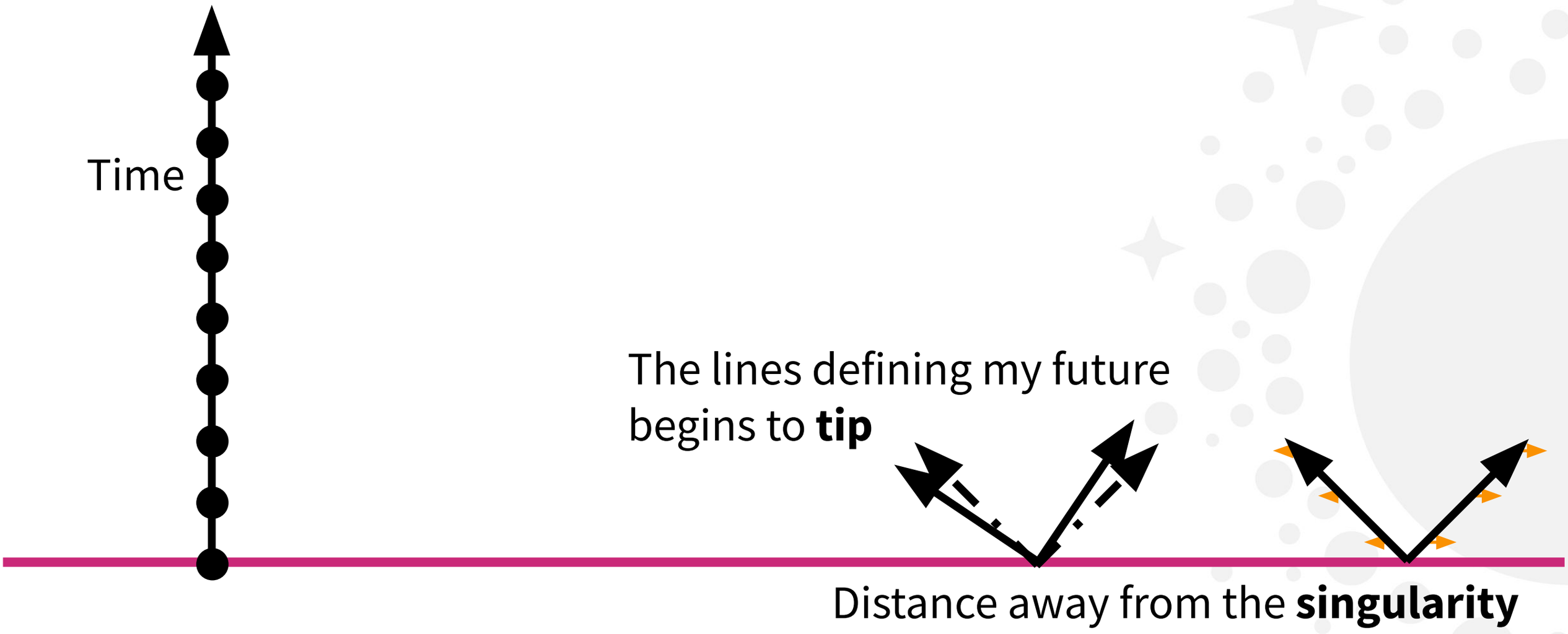


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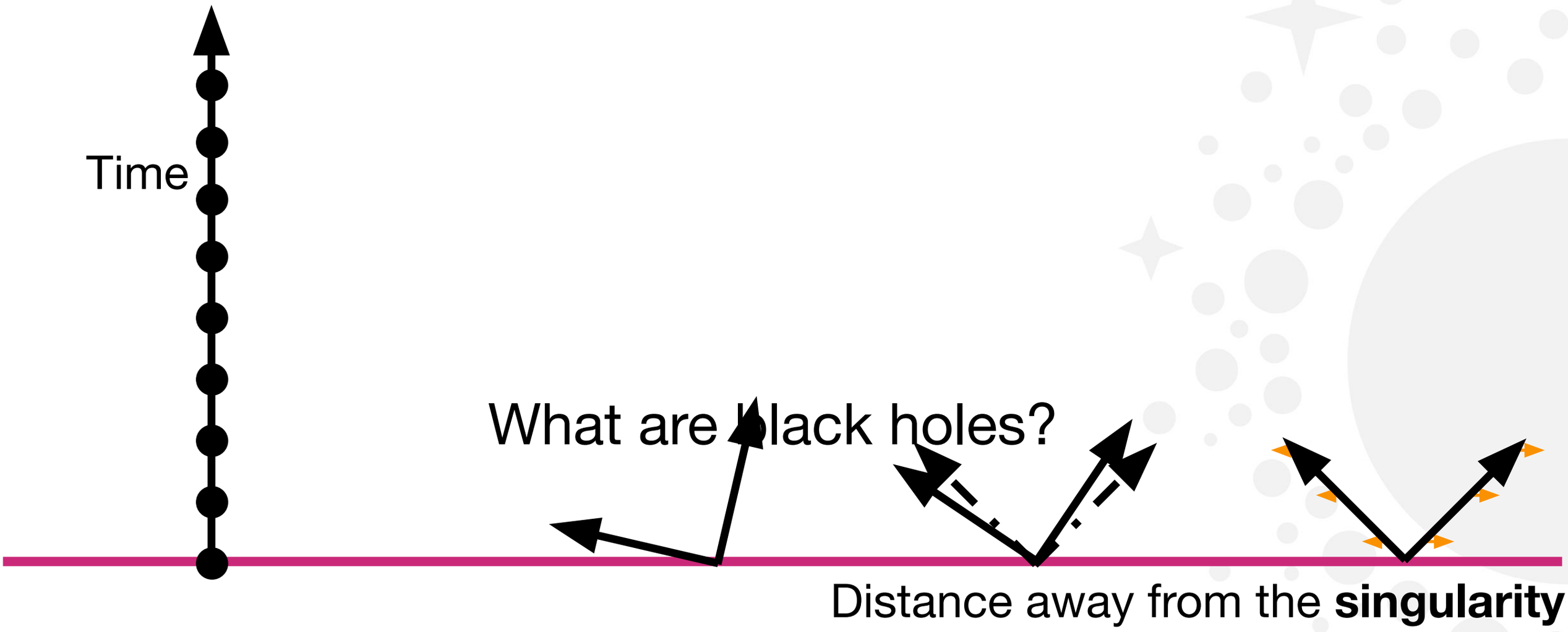


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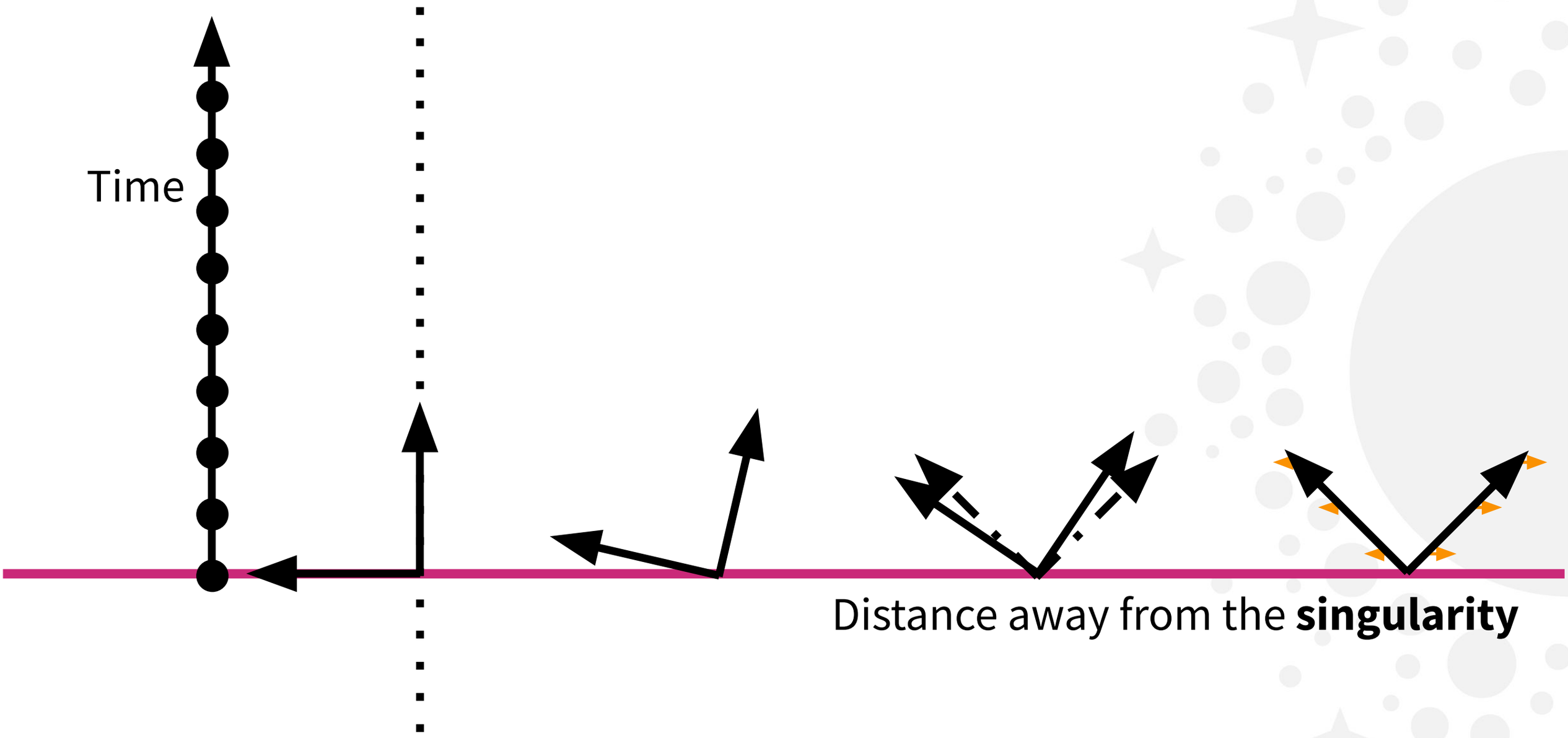

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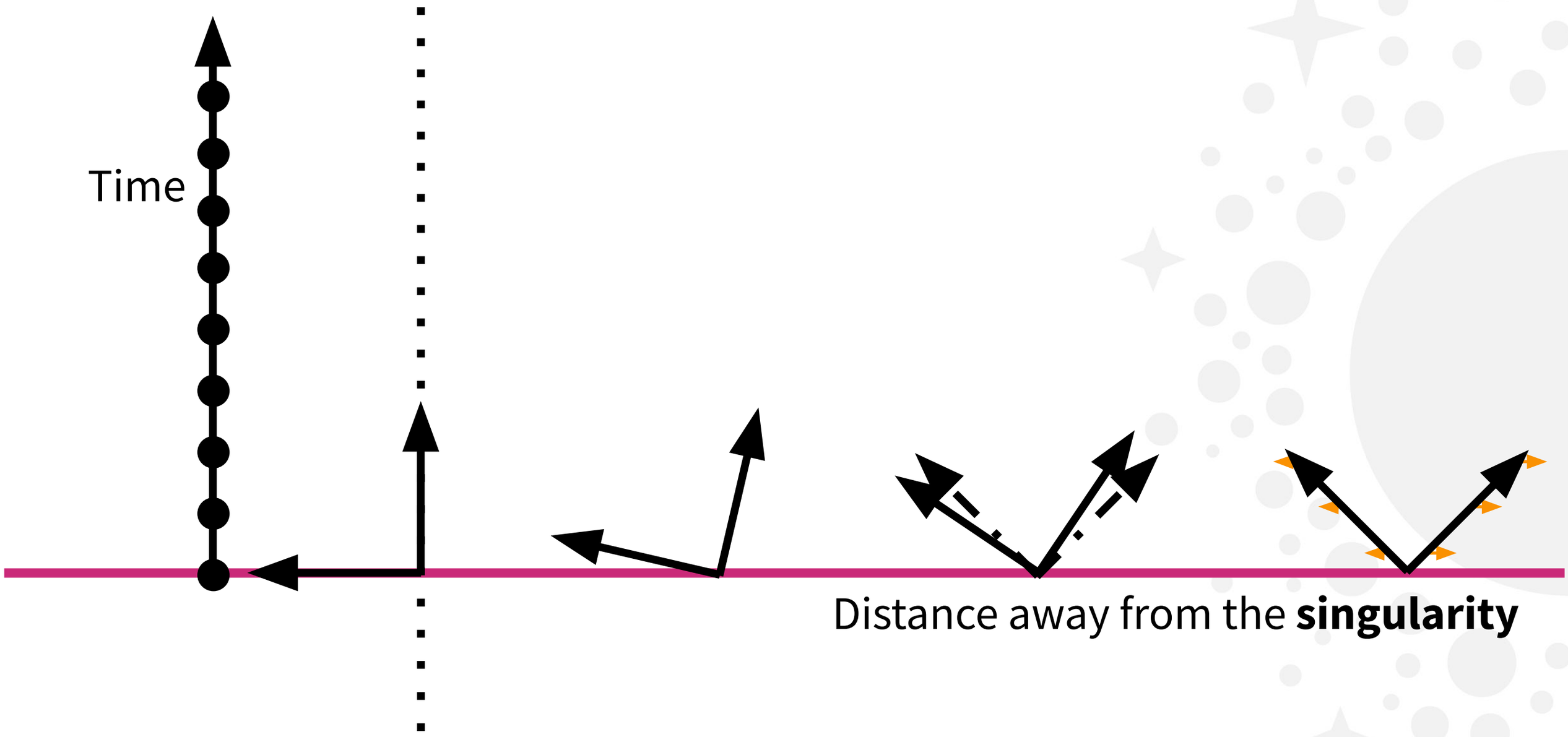


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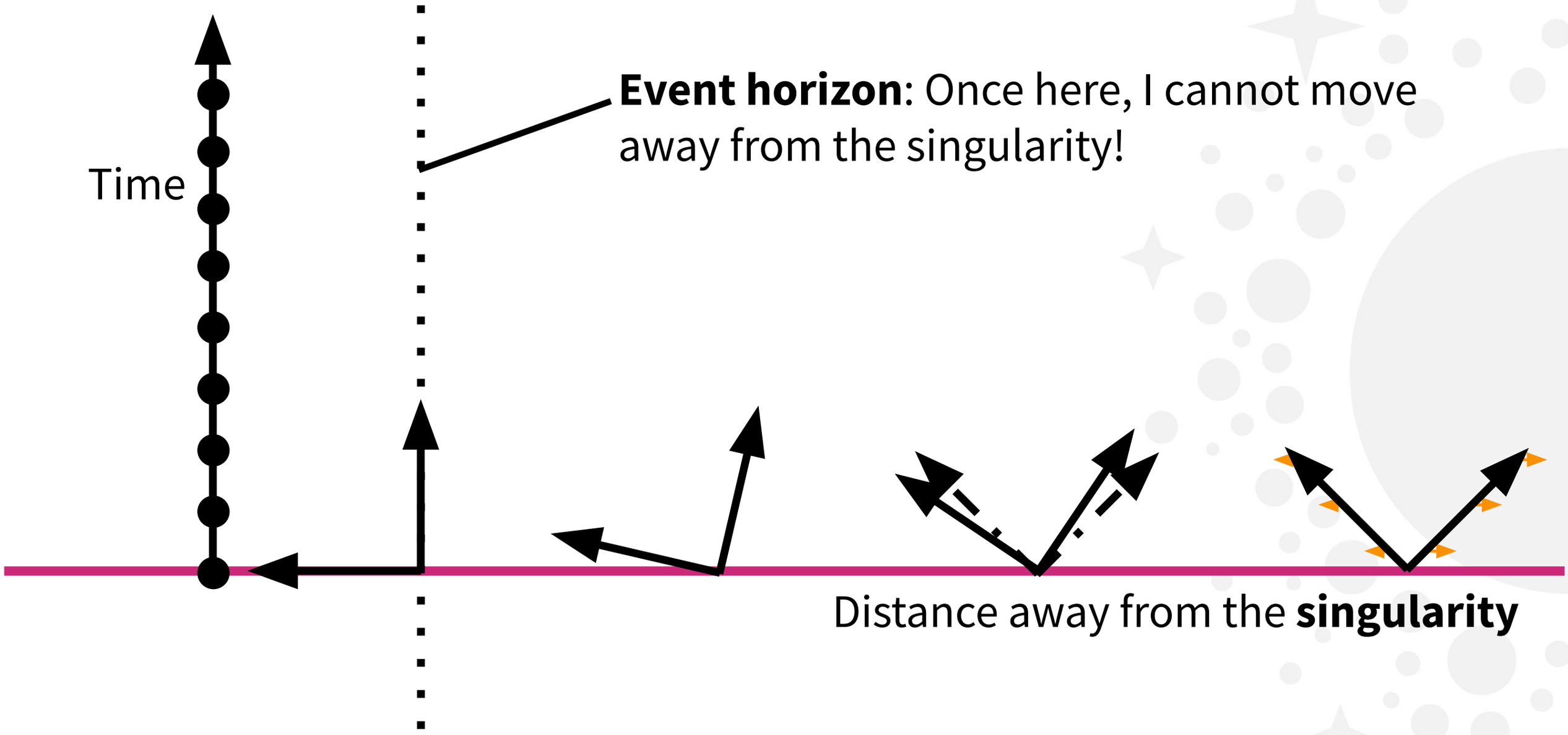


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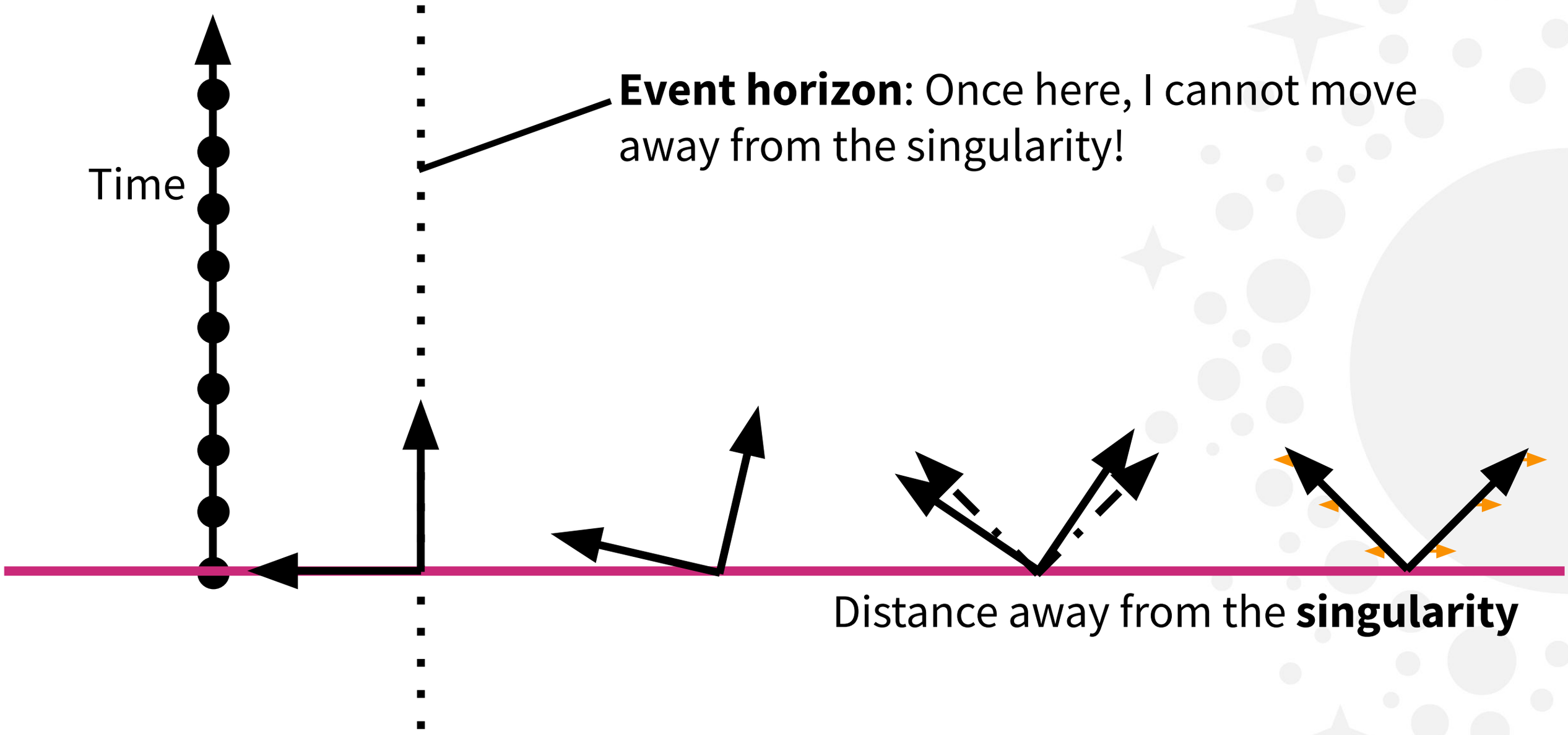


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In fact, in a technical sense, within the event horizon time and space switch places

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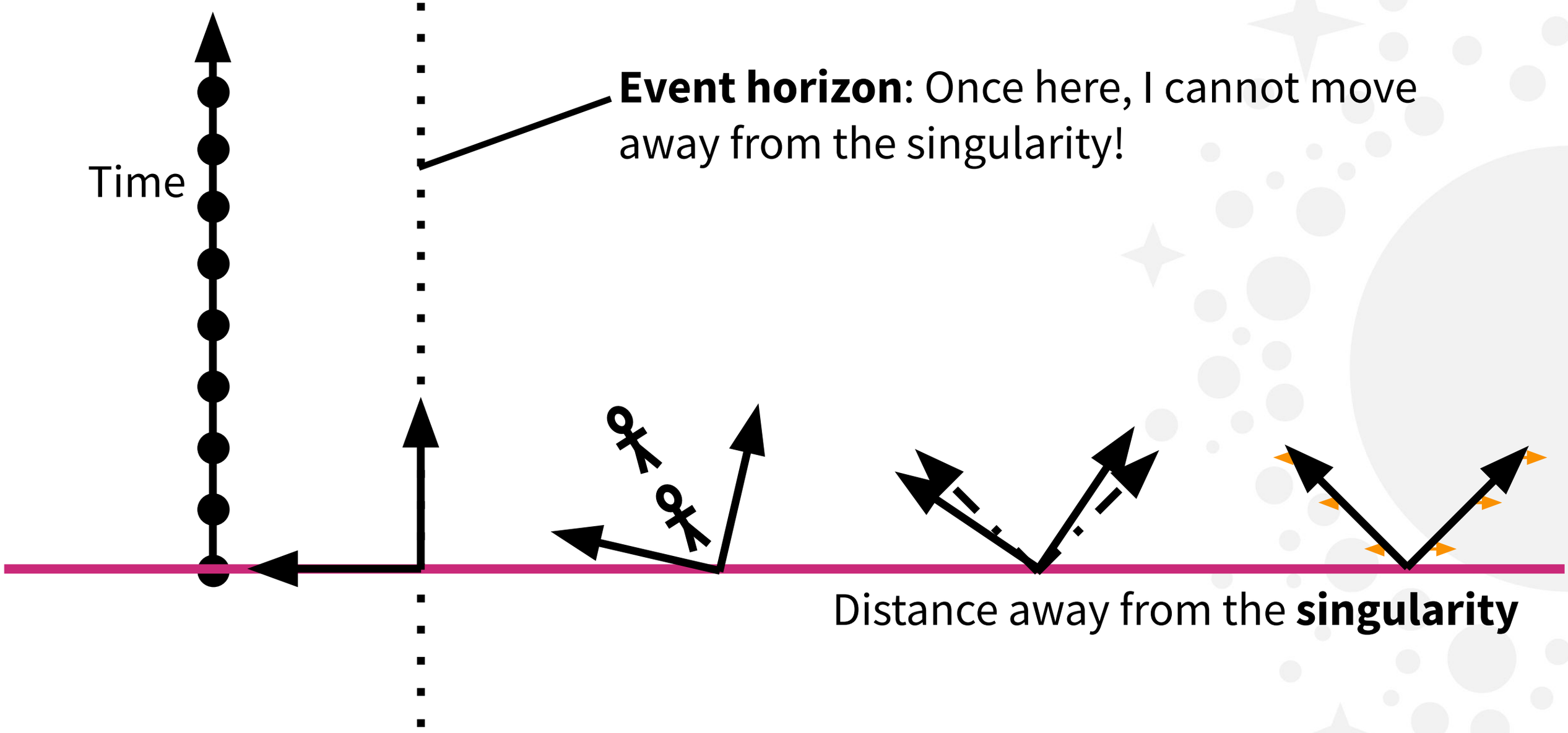


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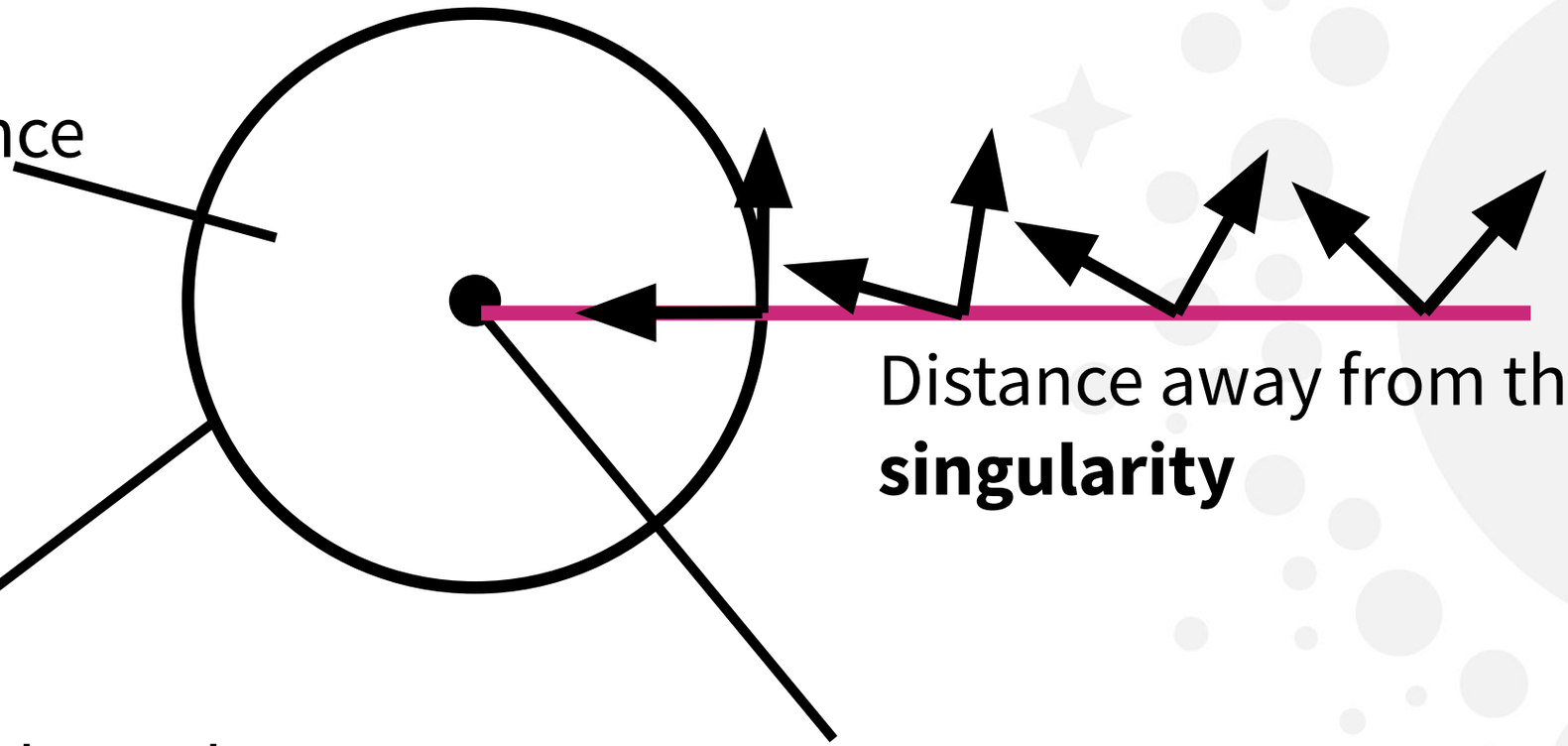


Distance away from the **singularity**

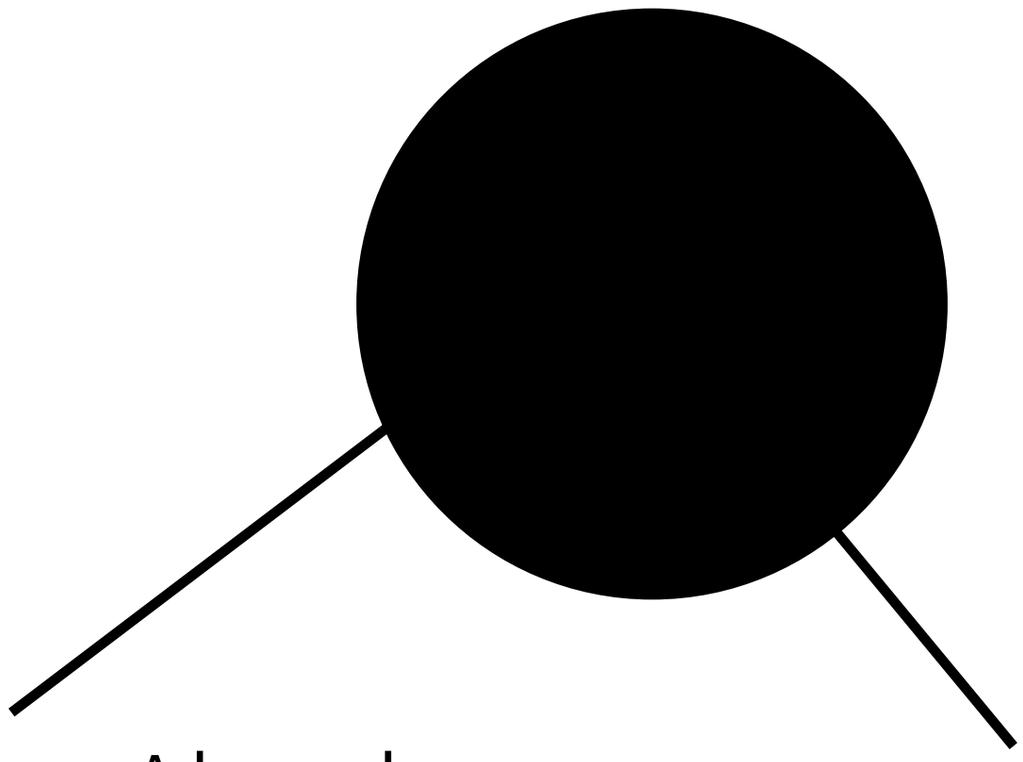
**Event Horizon**: A boundary where nothing can escape, not even light!

**Singularity**: A point of infinite “density”

# 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:



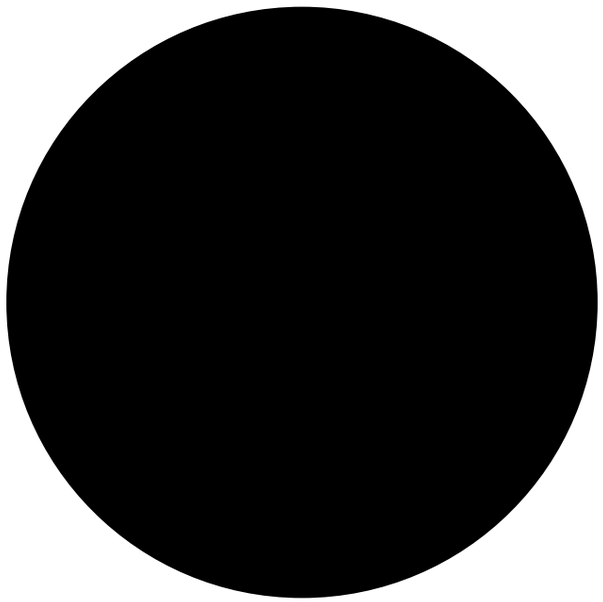
**Event Horizon**: A boundary where nothing can escape, not even light!

**Singularity**: hidden inside the event horizon

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

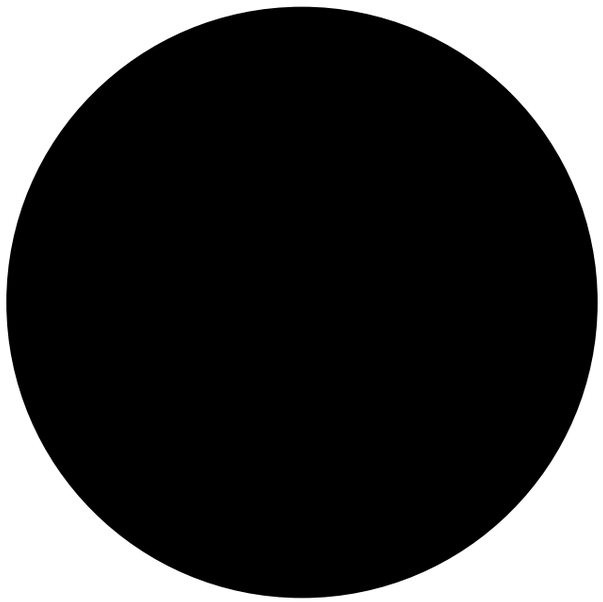
# How do we see black holes?

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



# How do we see black holes?

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



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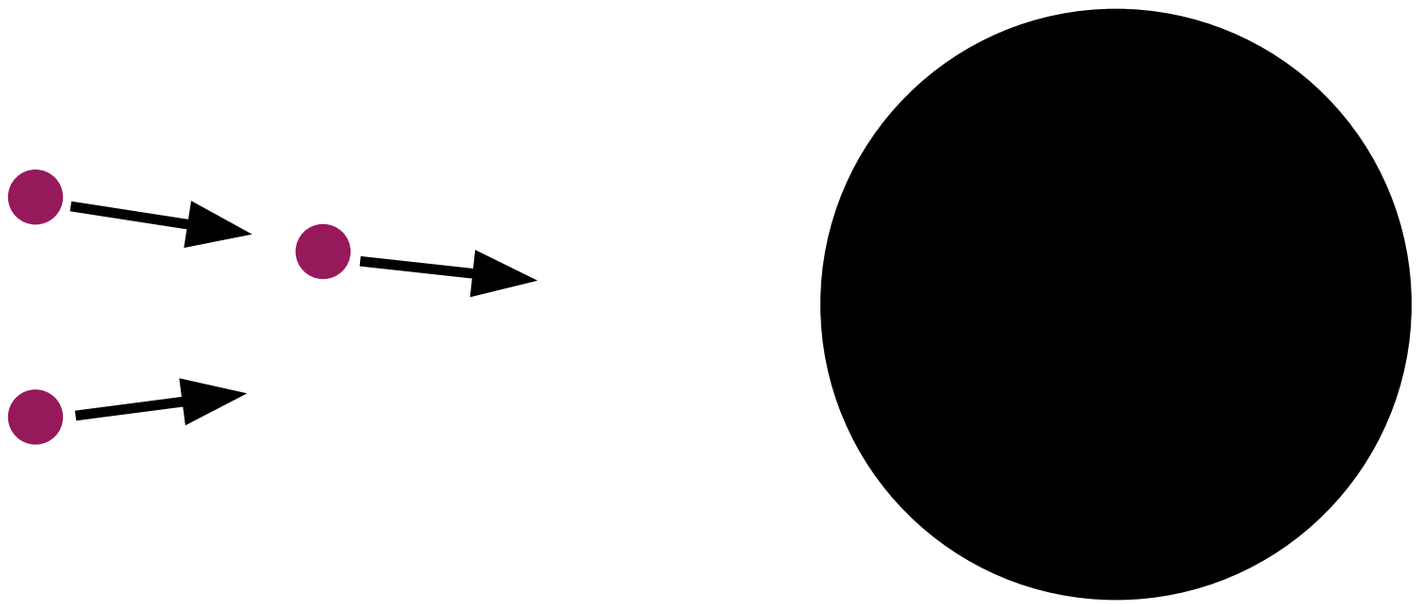

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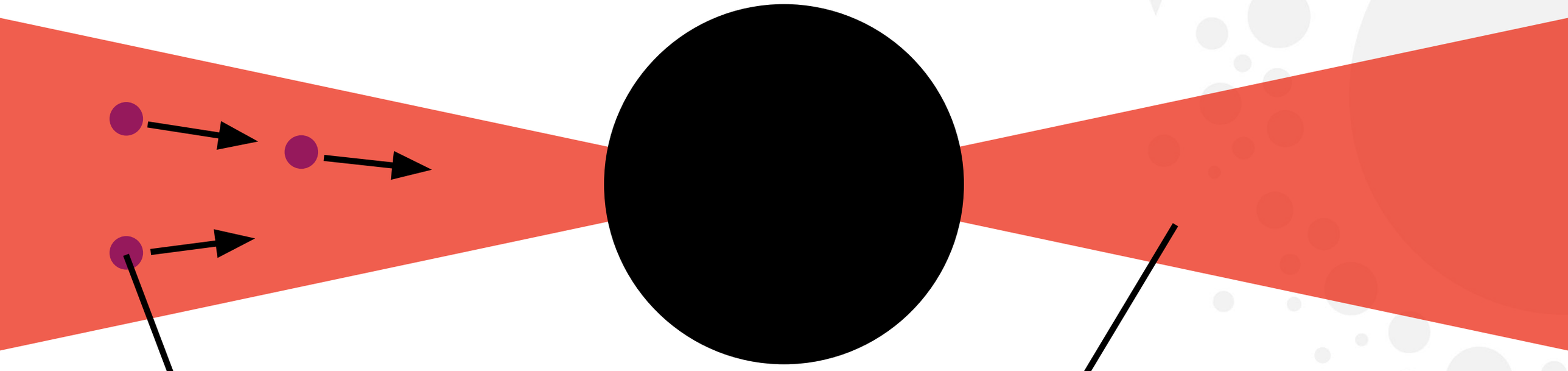
While a black hole is invisible, the region around it is **bright**

-) 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

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## 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?

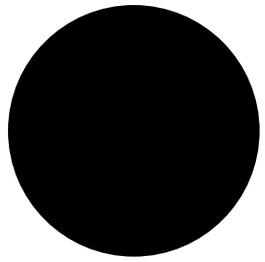
We can model black holes using general relativity

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

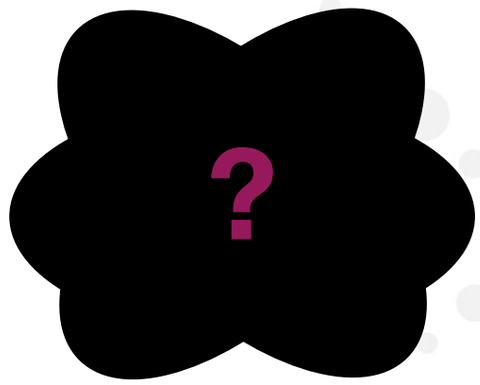
How do we know whether black holes in space are Einstein's black hole?

# Black Holes as Laboratories of Strong Gravity

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

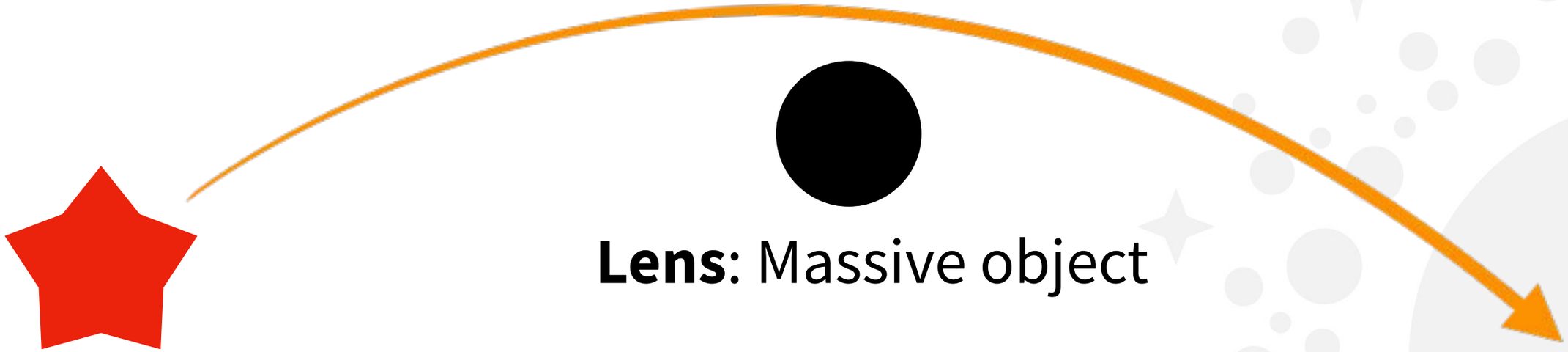


**Einstein’s black hole**: A black hole as we know it




?!?!?

## Gravitational lensing



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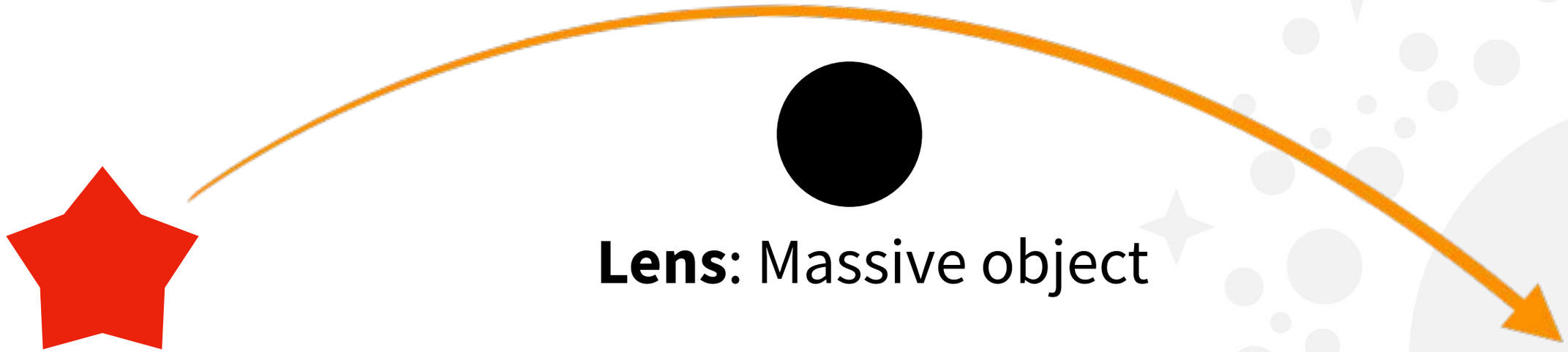
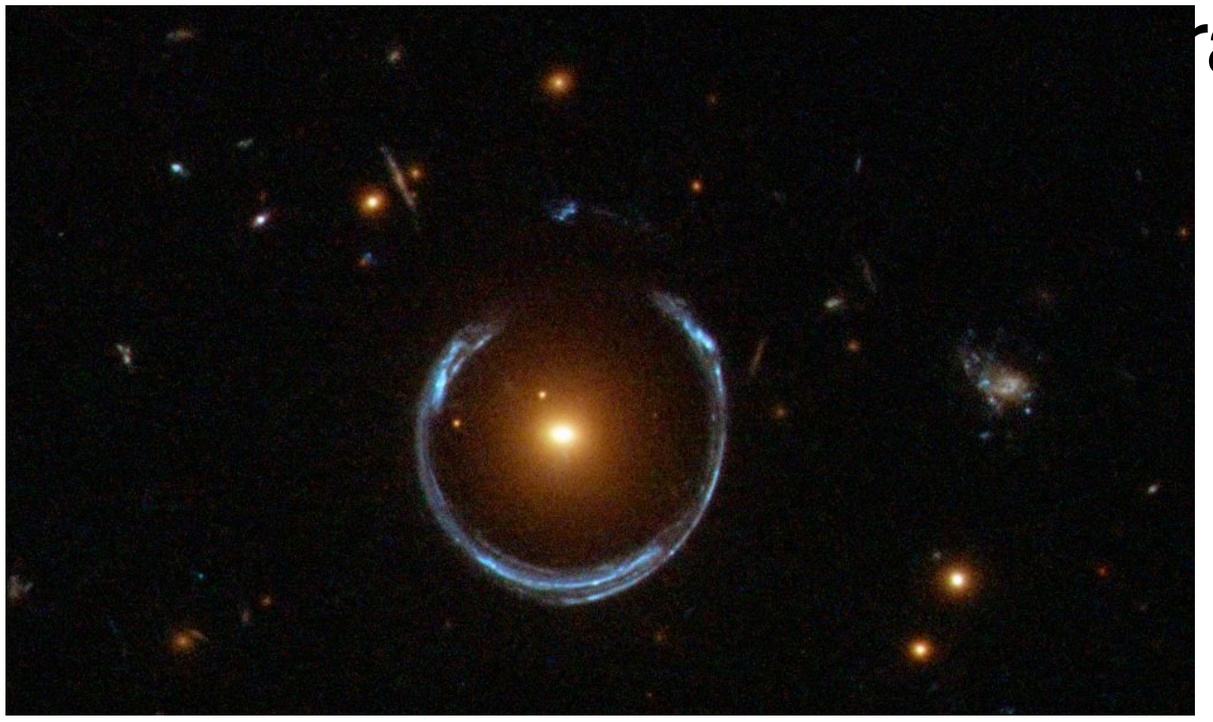


**Lens**: Massive object



Images credit: NASA/Stsci - Hubble Space Telescope

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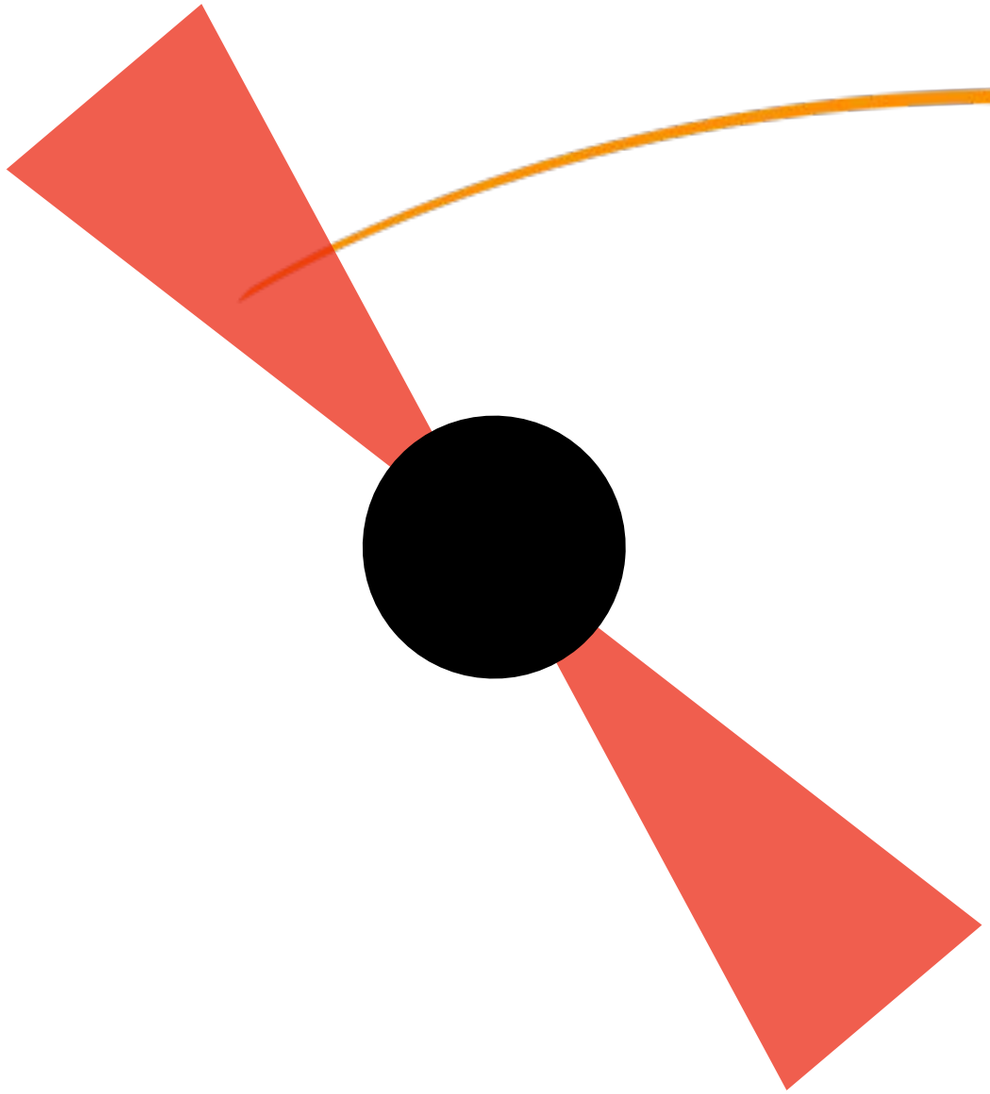
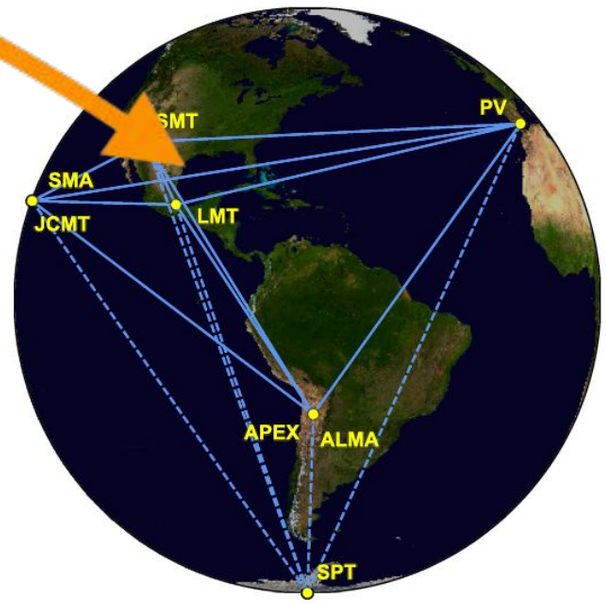
The black hole lenses **its own accretion disk!**





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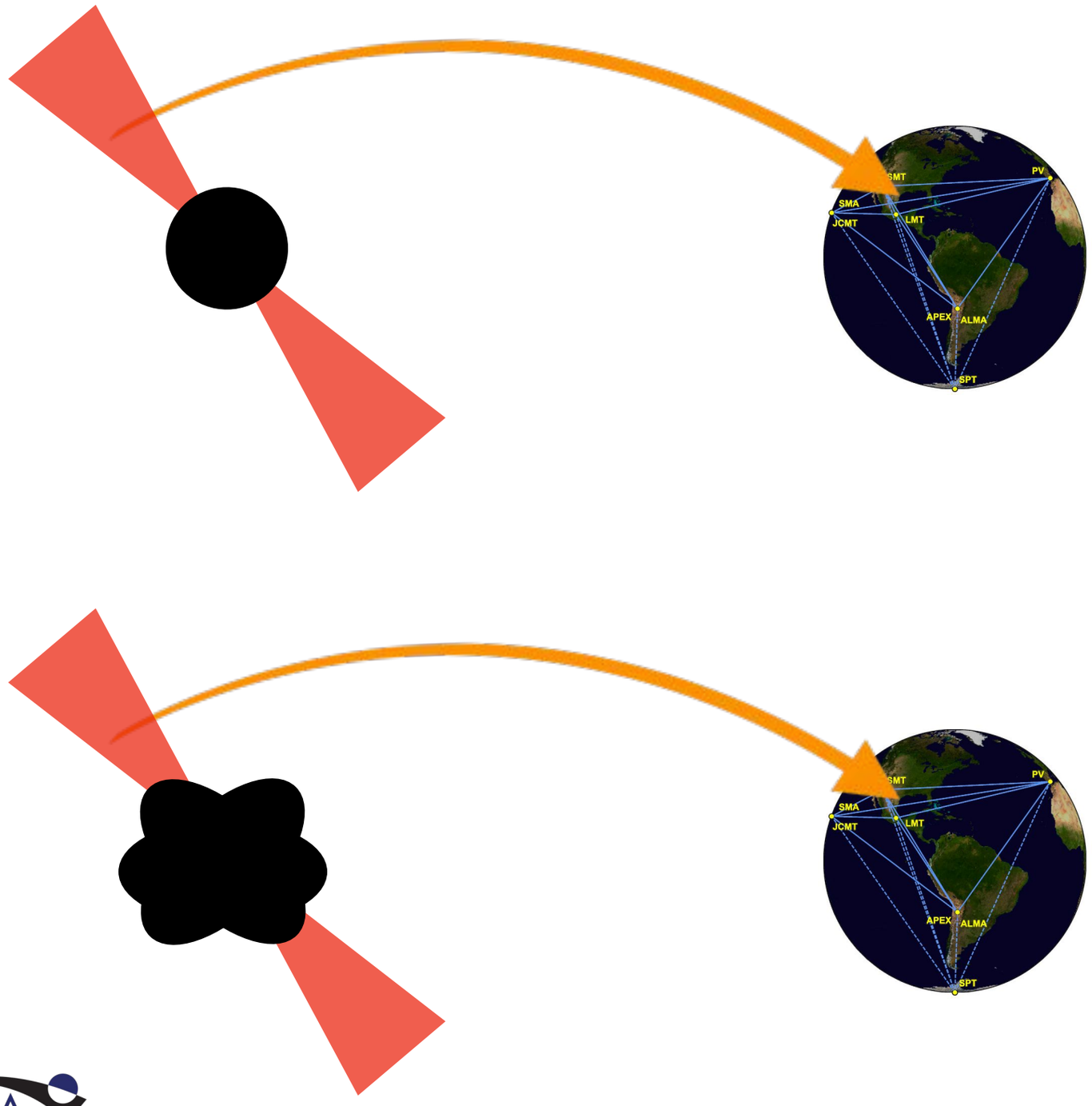


Produces different looking images!

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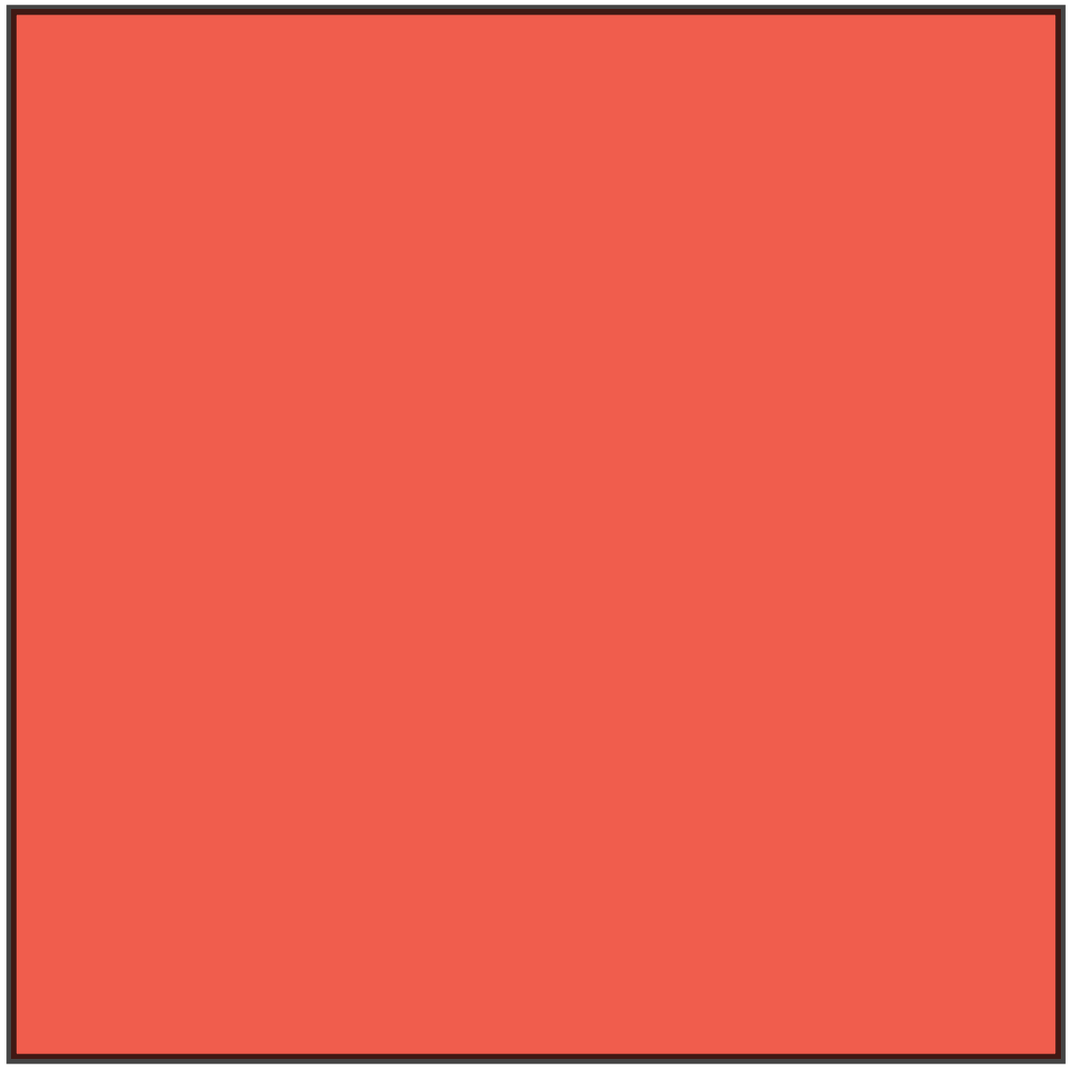

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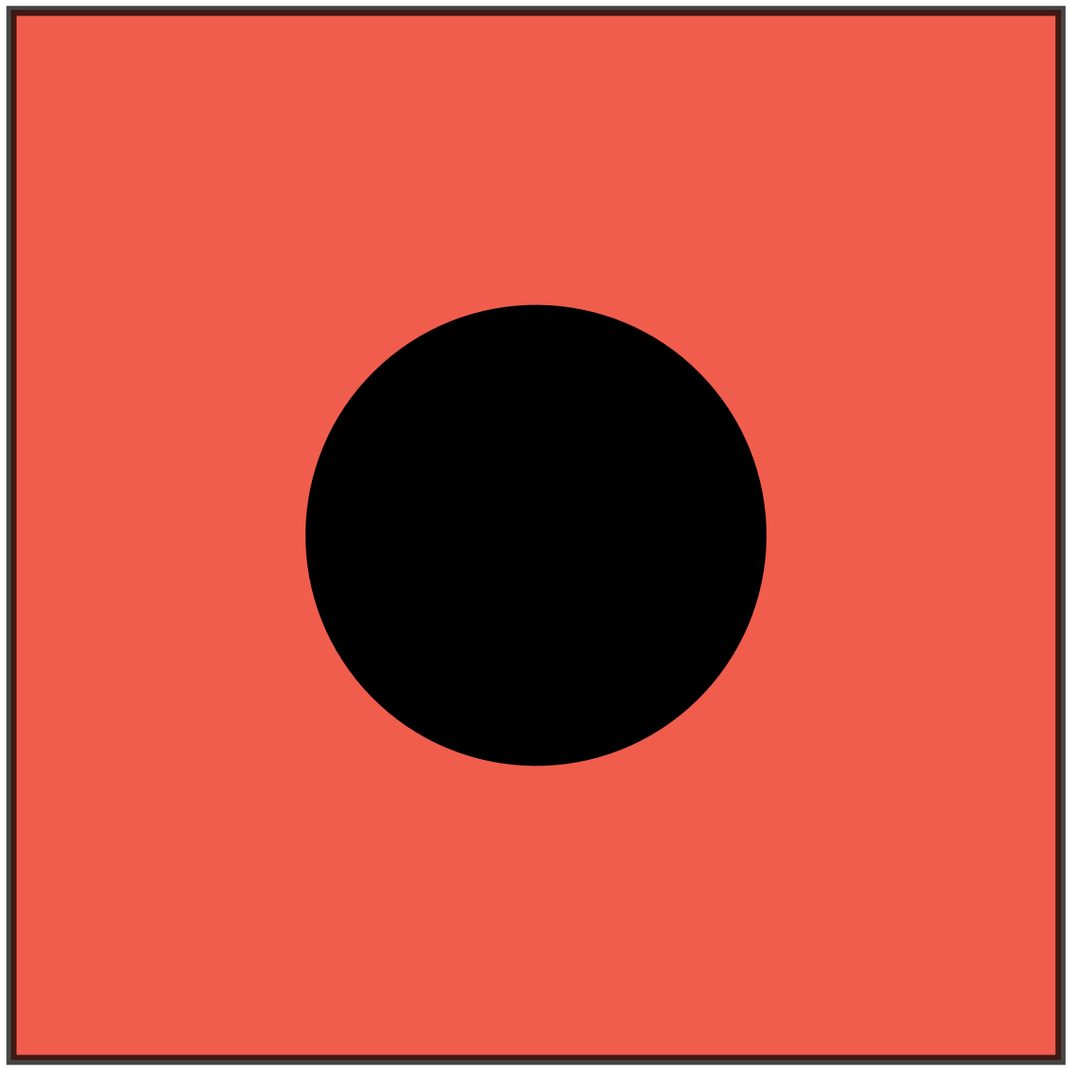

Images credit: Hotaka Shiokawa

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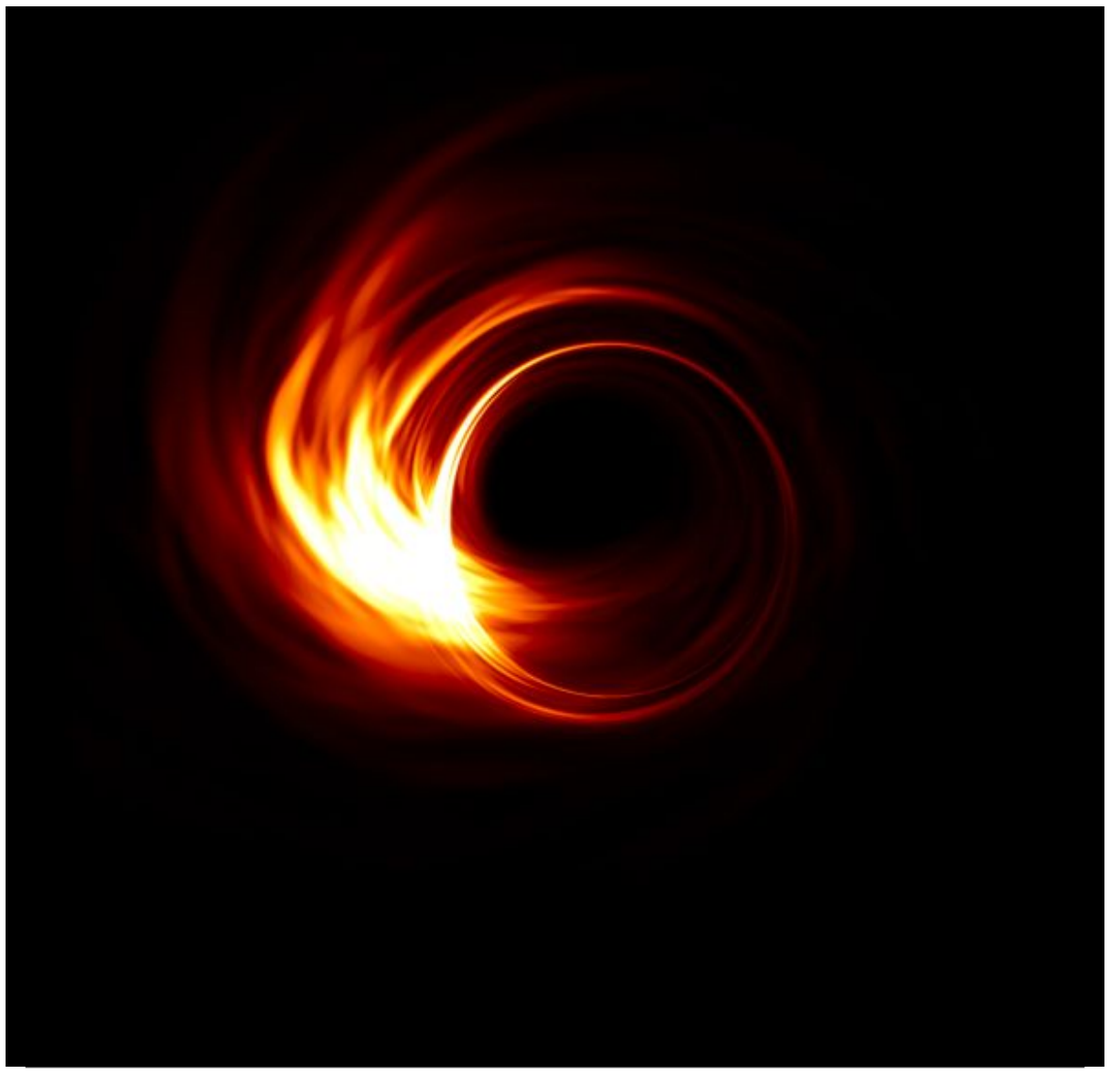

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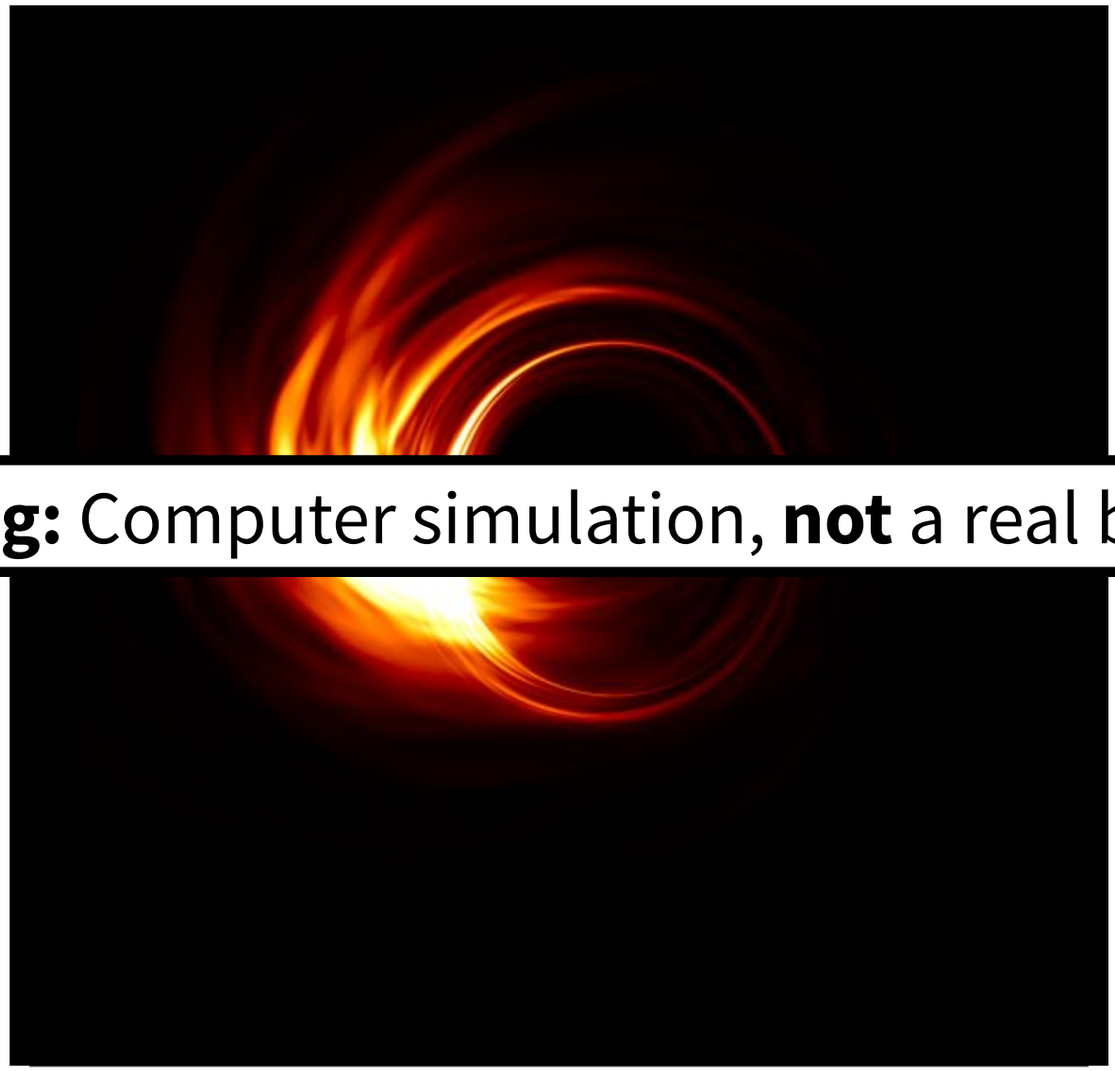

**Warning:** Computer simulation, **not** a real black hole!

Image credit: EHT Collaboration, Hotaka Shiokawa

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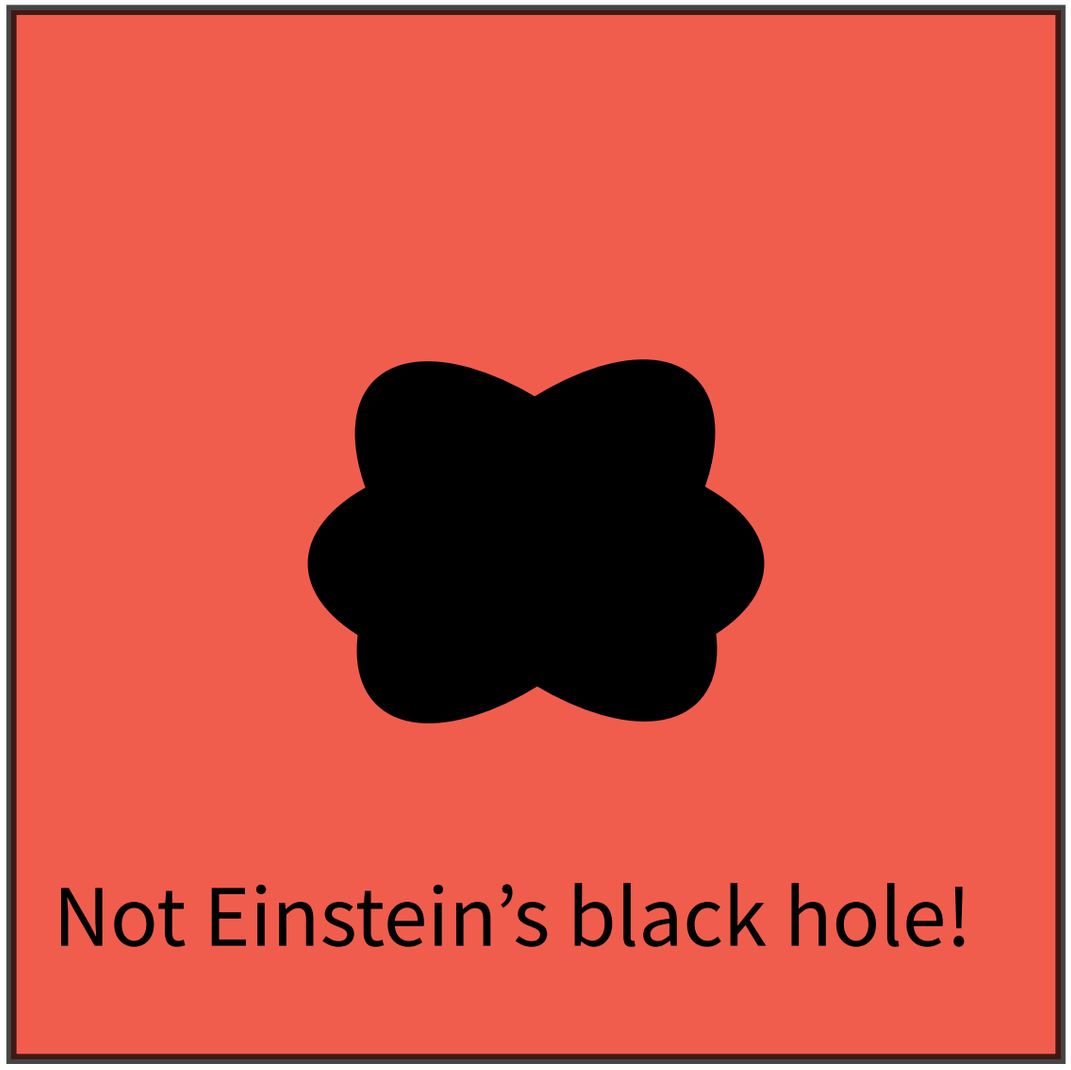

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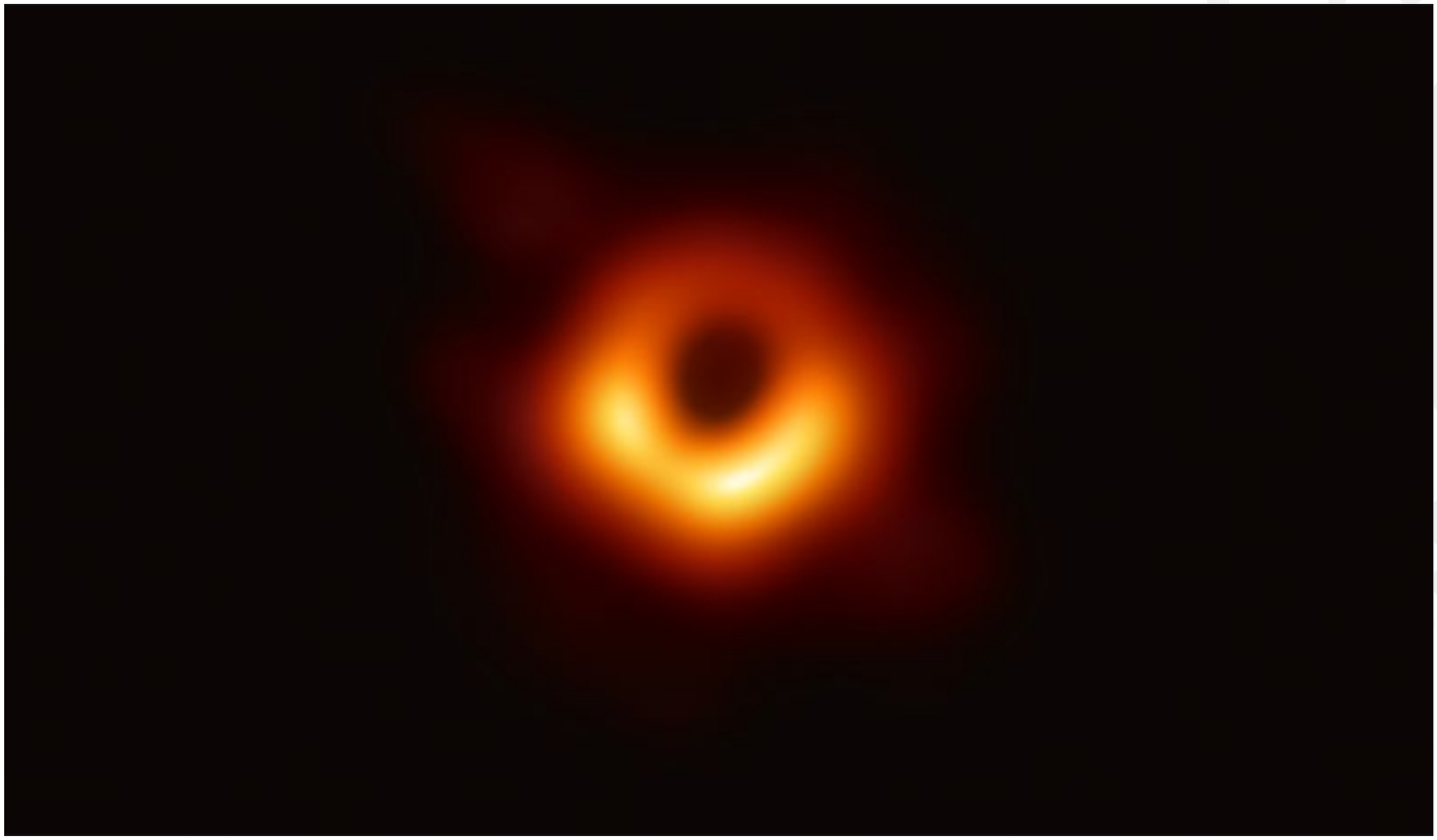

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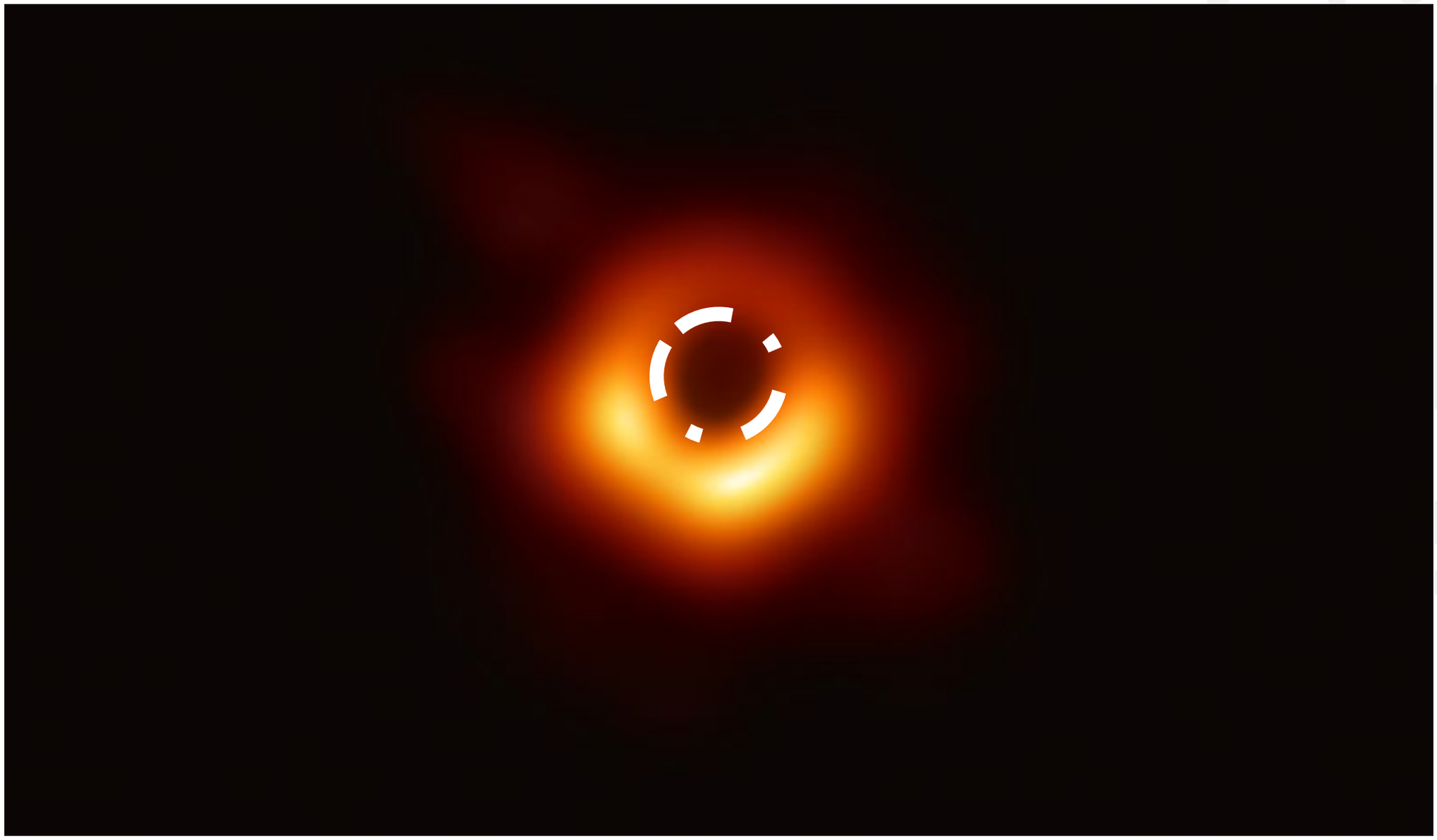

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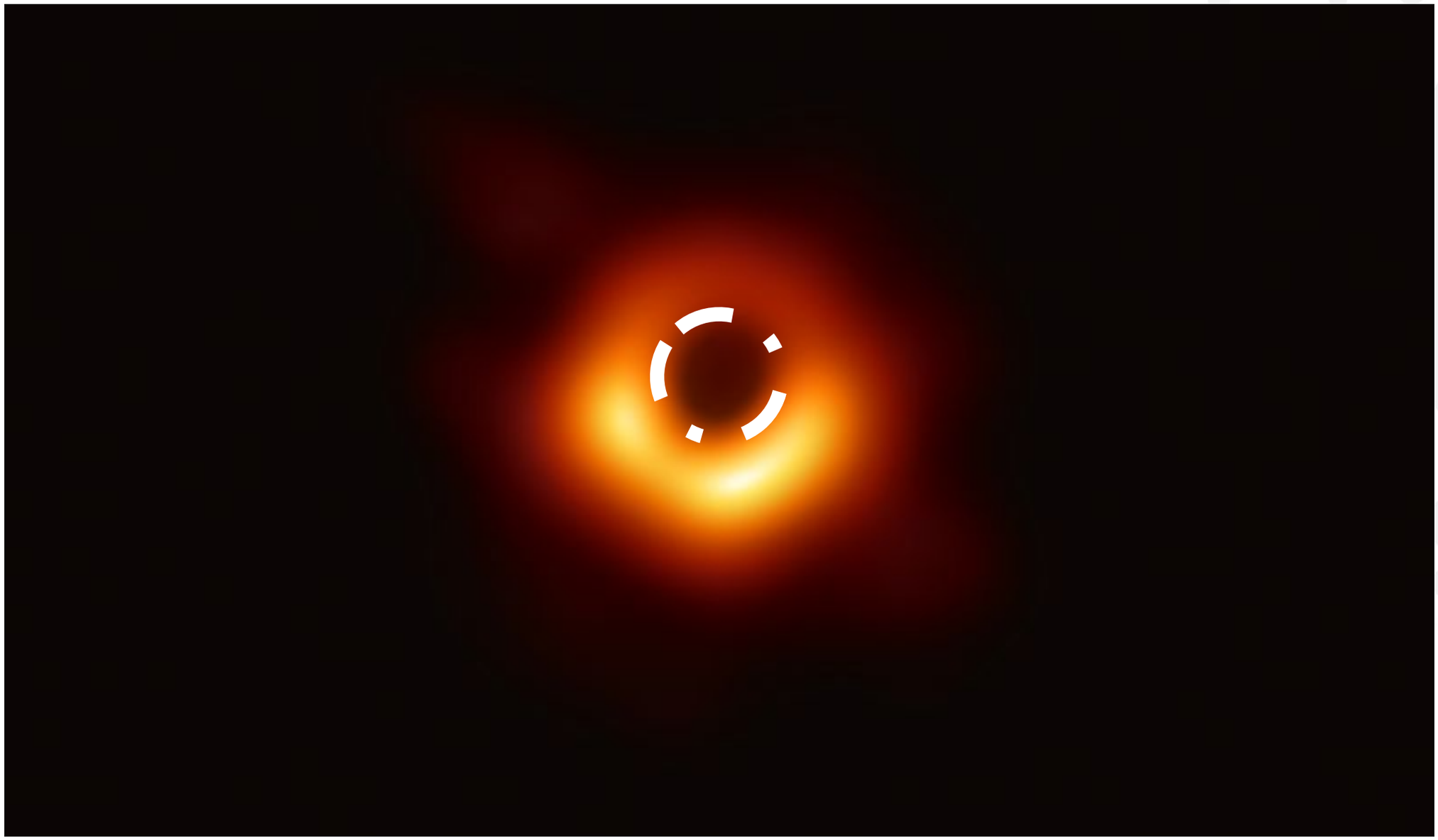

So far, Einstein is **vindicated**!

# Thank you!

# TEEN ASTRONOMY *Café* – To Go!

# How do we see black holes?

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

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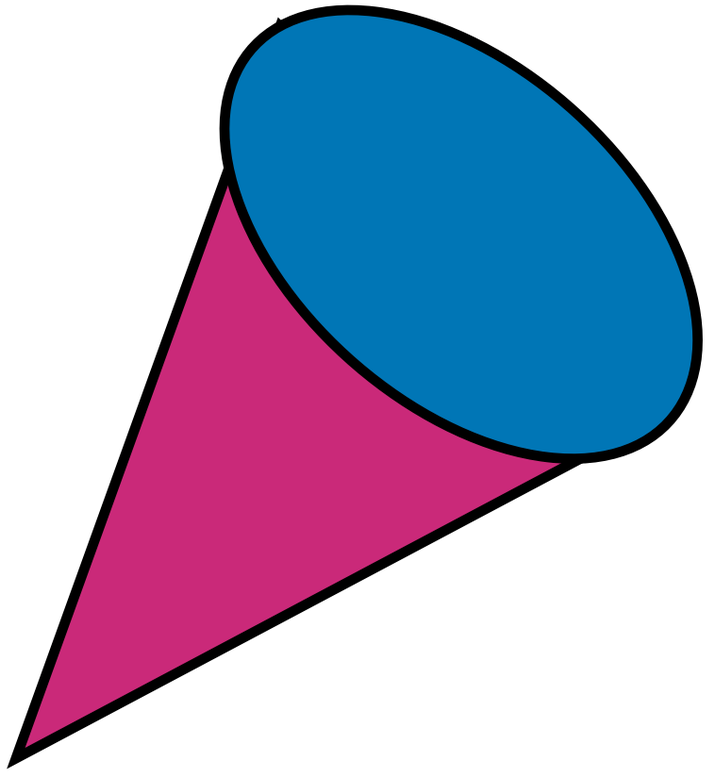
**M87's BH**: 50 million light-years away, ~10s of microarcseconds diameter

# How do we see black holes?

## Can I resolve something with my telescope?



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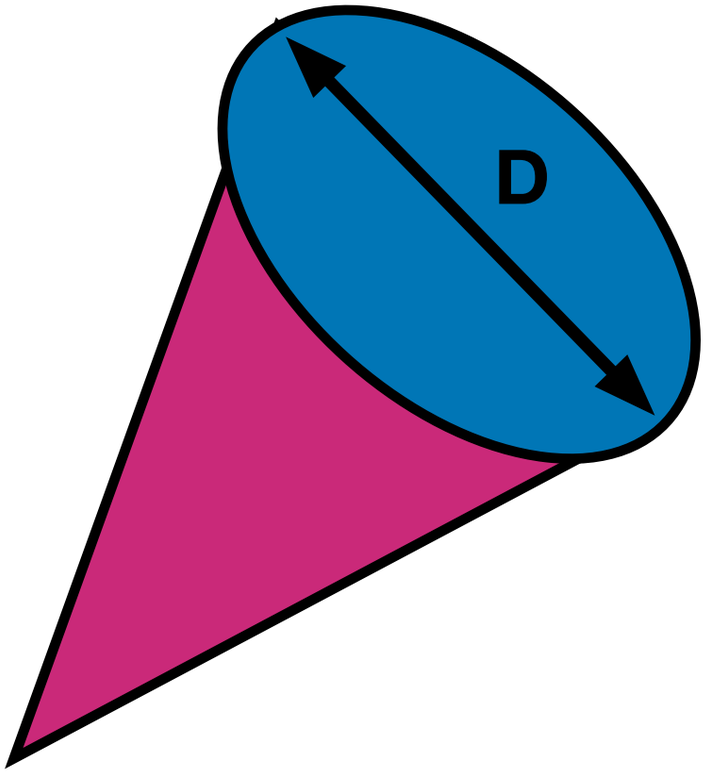
The **larger** the telescope, the **larger** the resolution!




*For the experts: In addition, the **smaller** the wavelength, the **larger** the resolution

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**Plugging in the numbers**: Need a telescope the size of the Earth!

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Image credit: SMT, SPT

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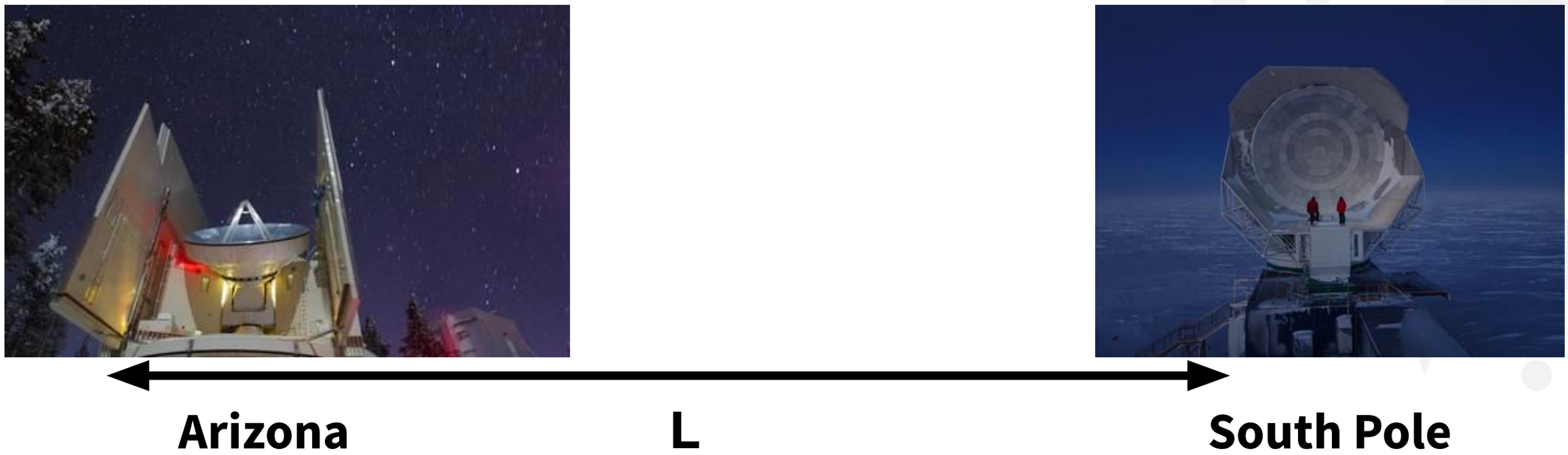


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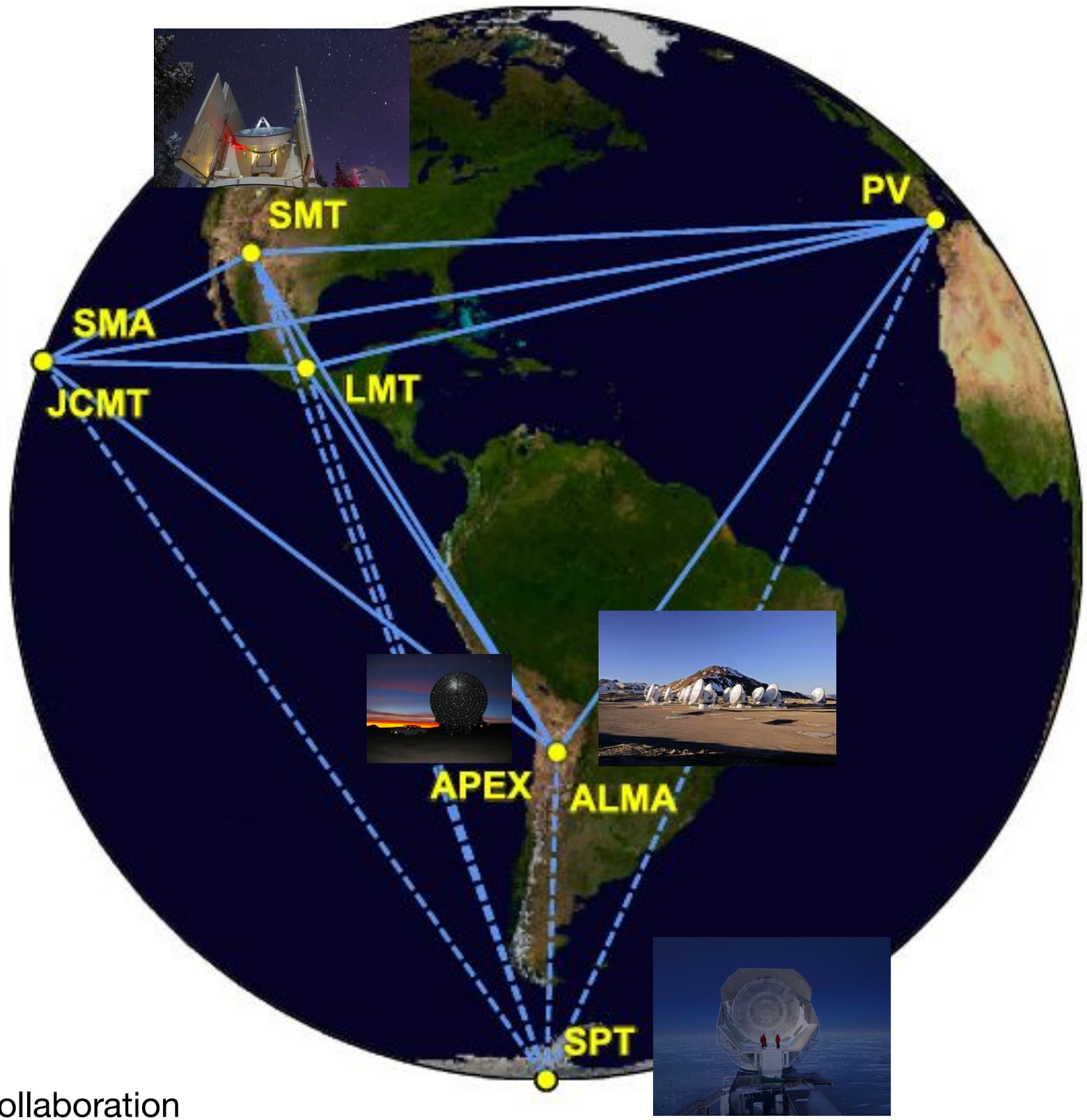


Image credit: EHT collaboration

# How do we see black holes?




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







Image credit: EHT collaboration

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In addition it requires the following to be true:

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

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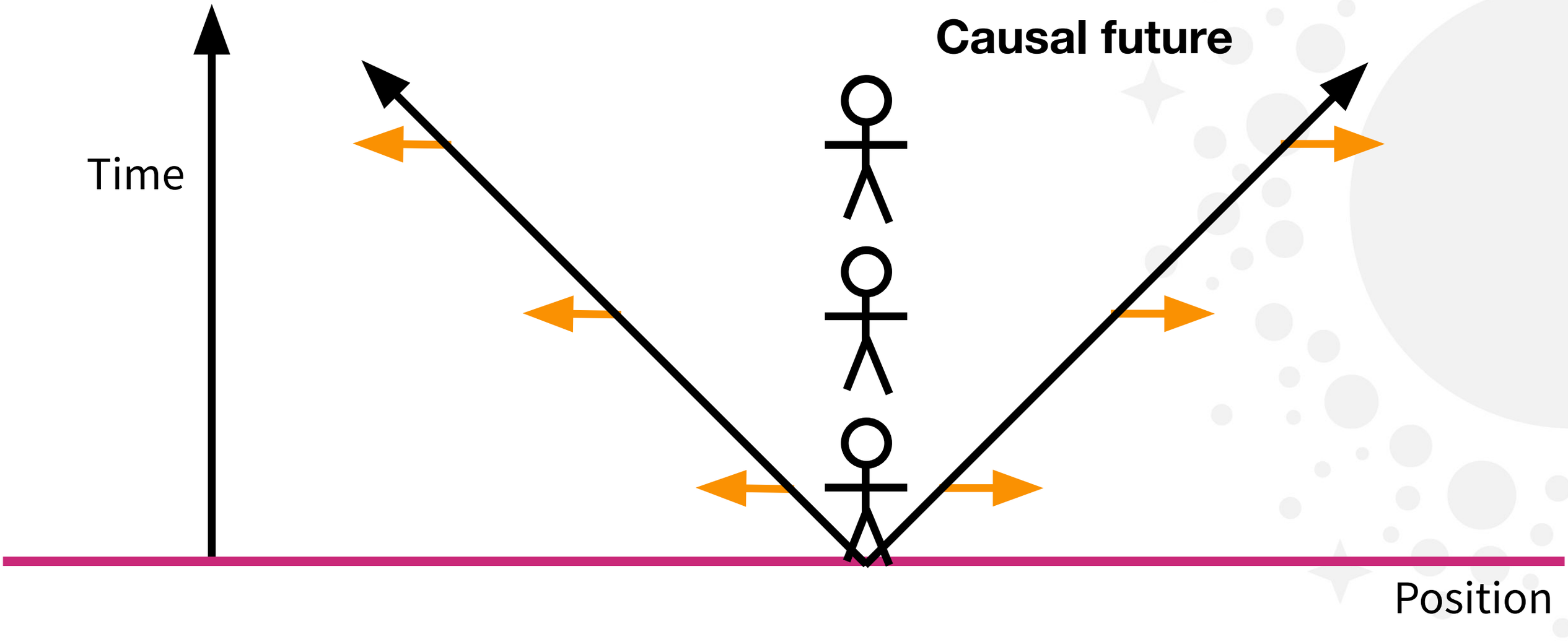
1) There is no closed timelike loop (no time travel)



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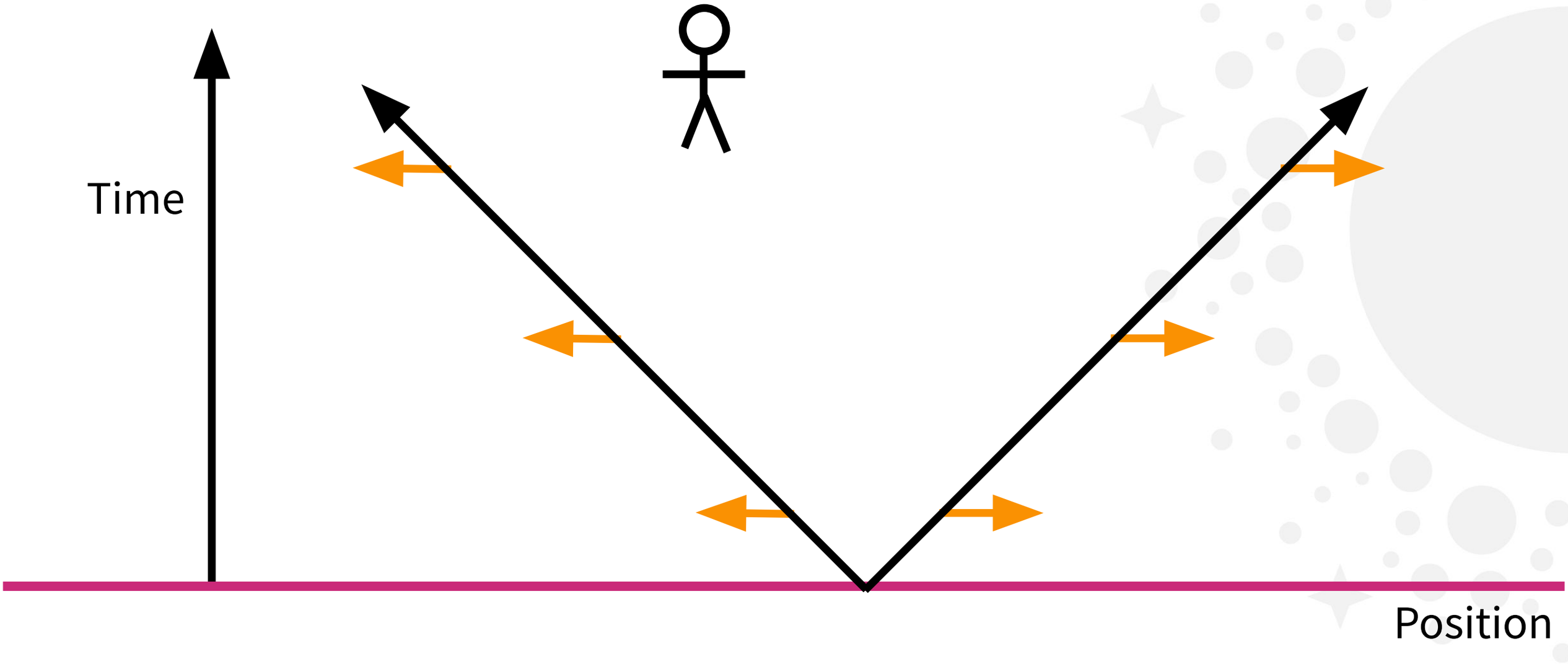

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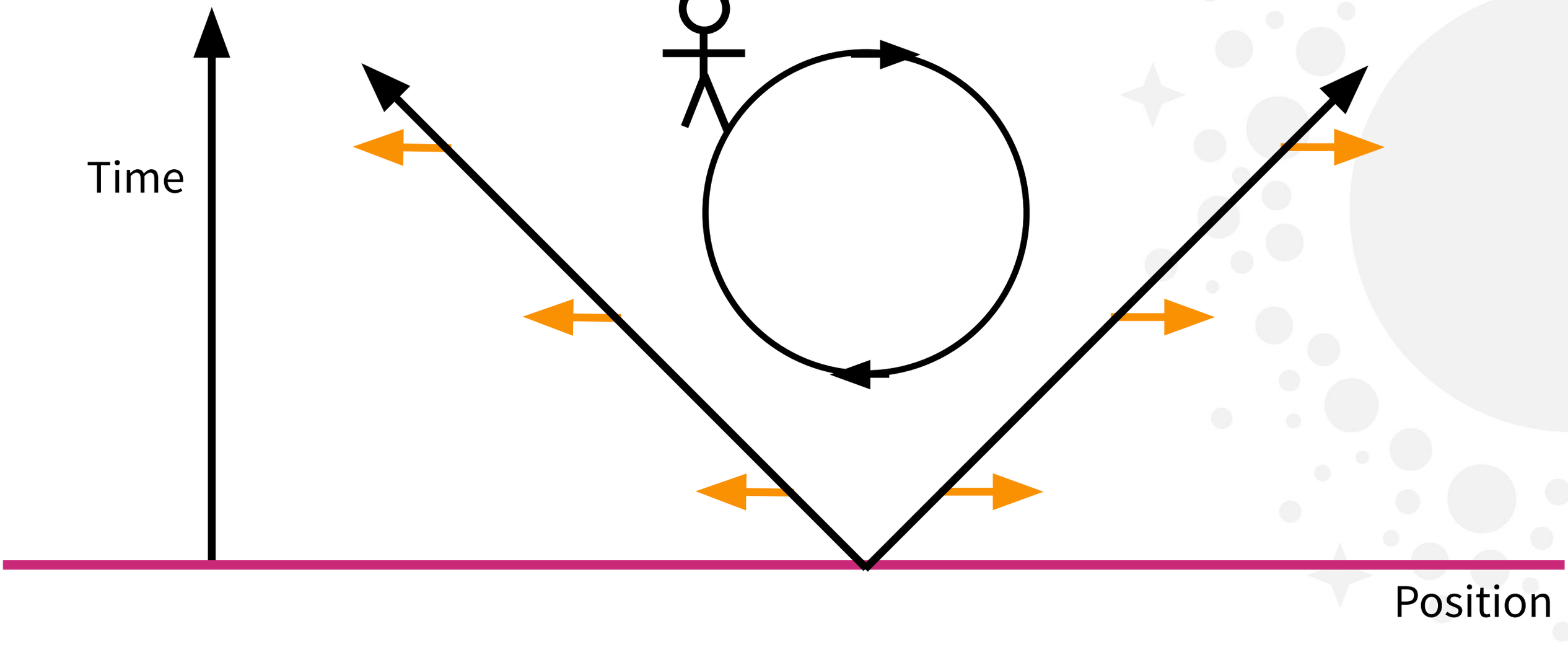

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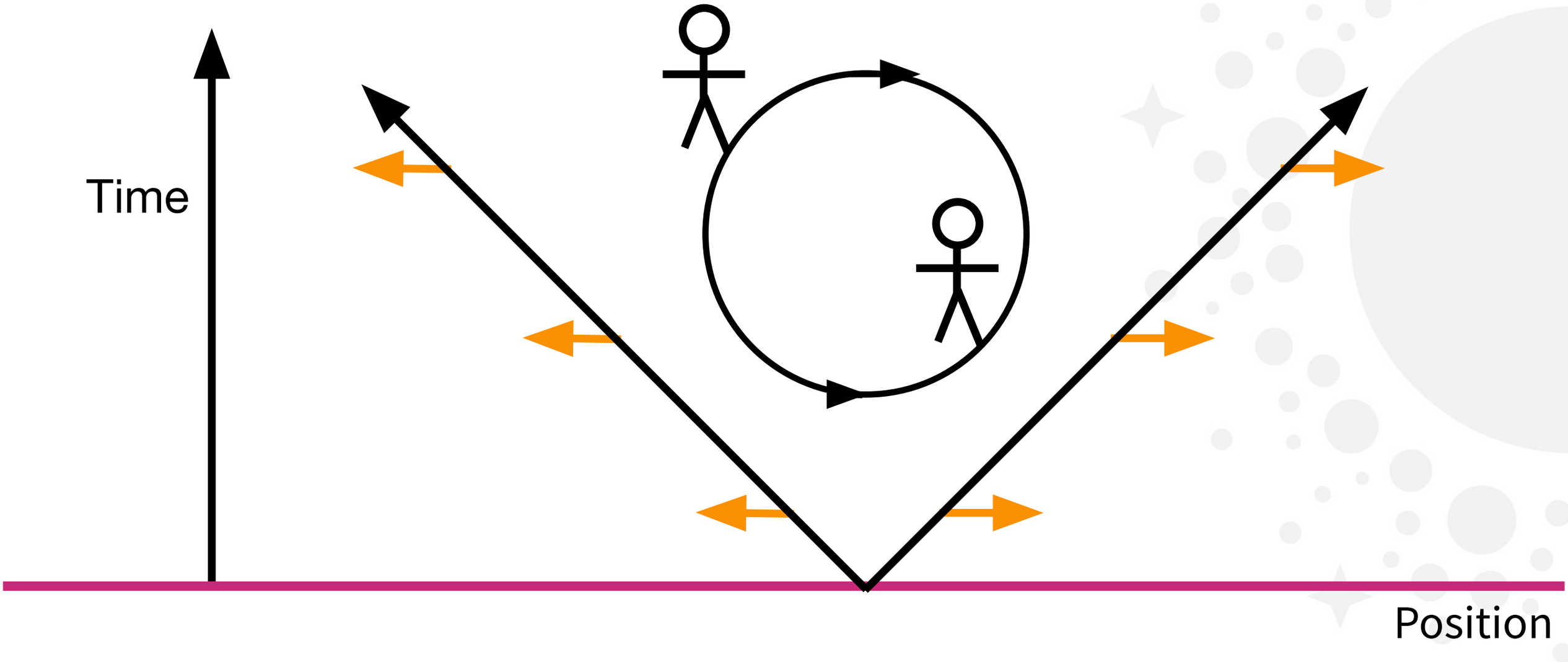
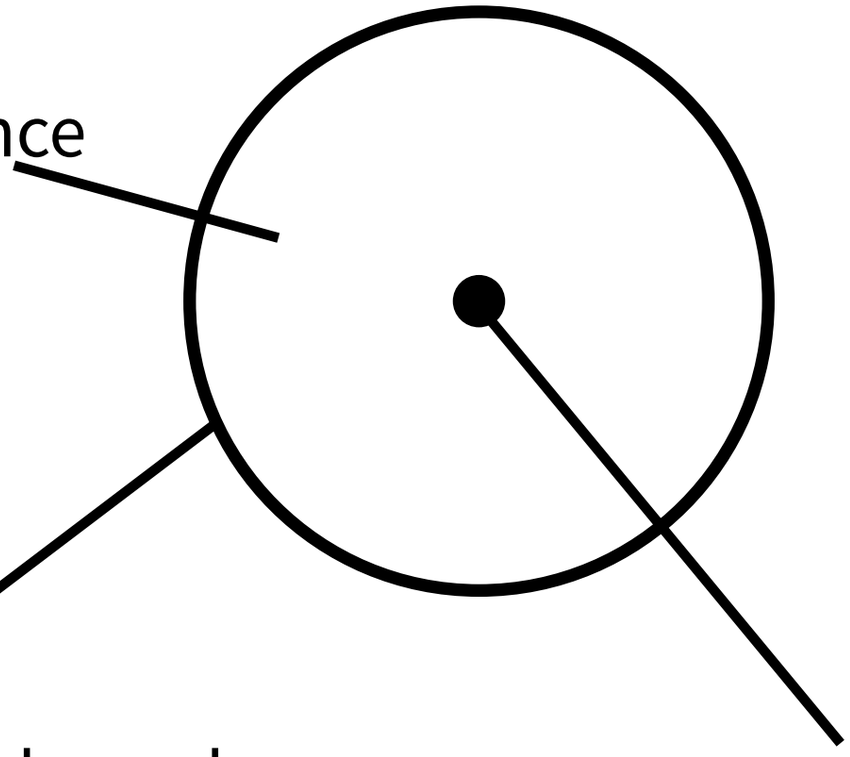


2) Nature abhors singularities without event horizons

**Black Hole Interior**: Nothing can get out once inside



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

**Singularity**: A point of infinite “density”

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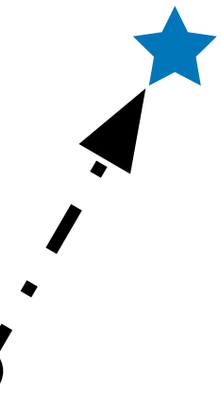

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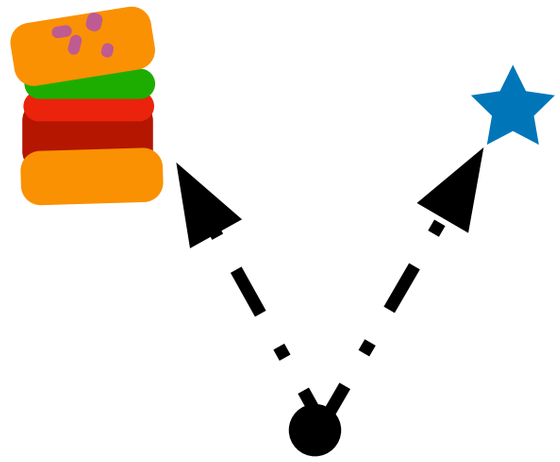

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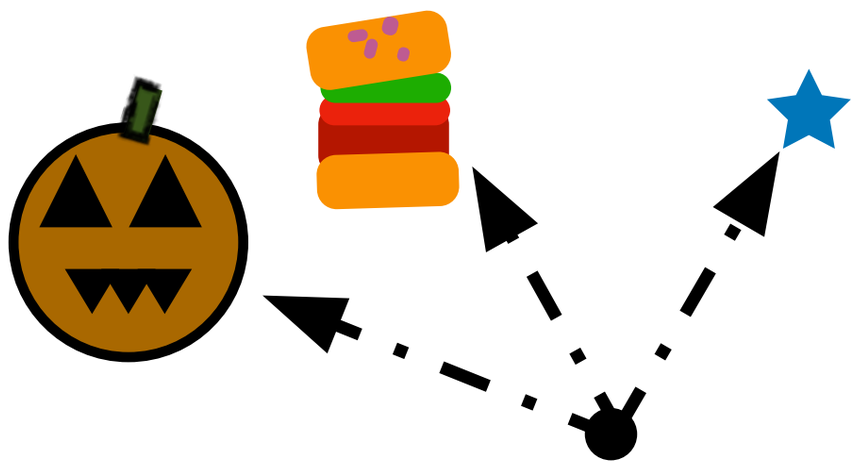

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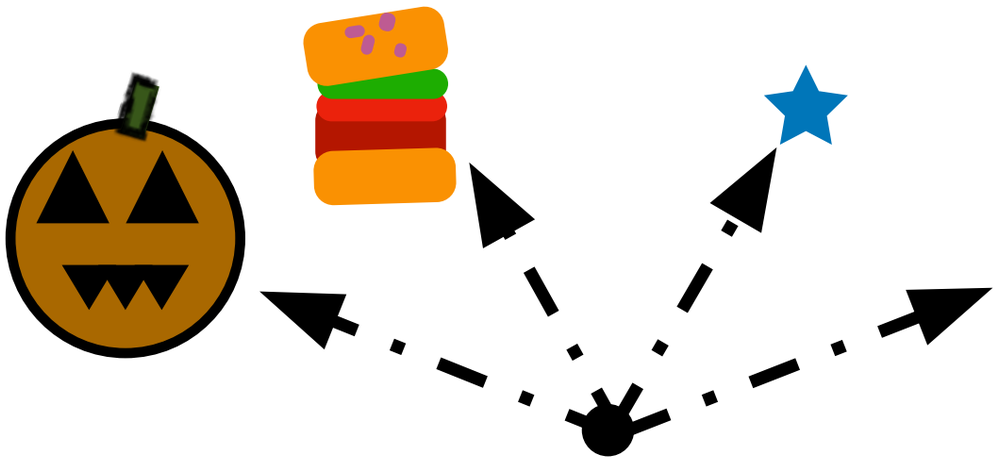

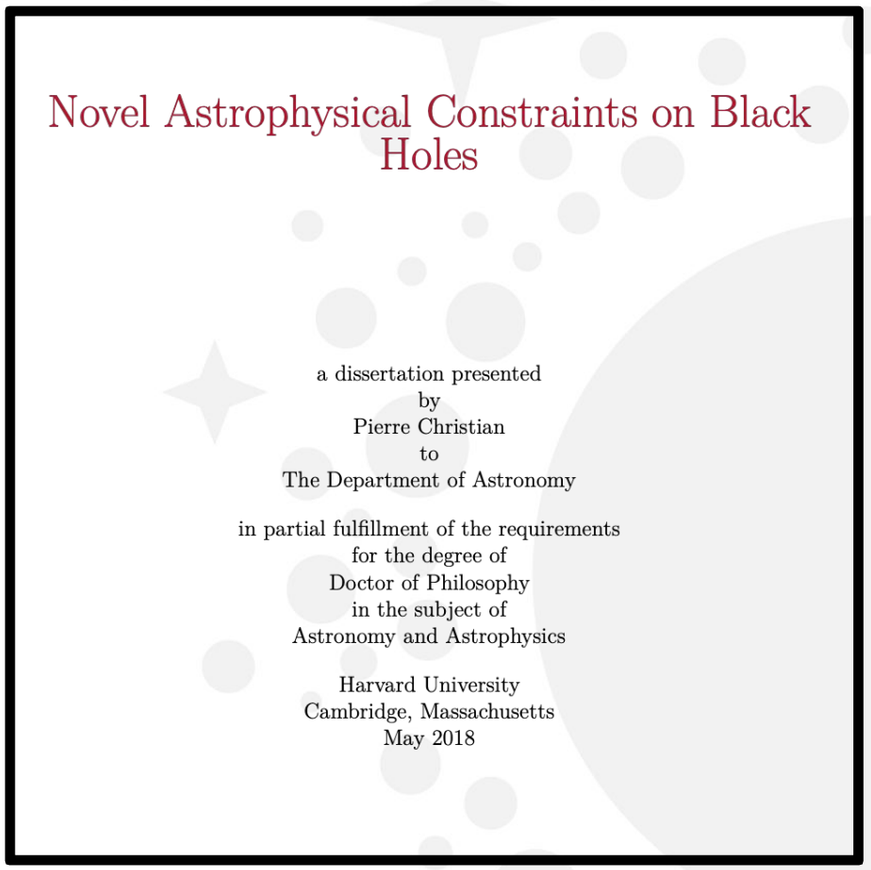

Novel Astrophysical Constraints on Black Holes

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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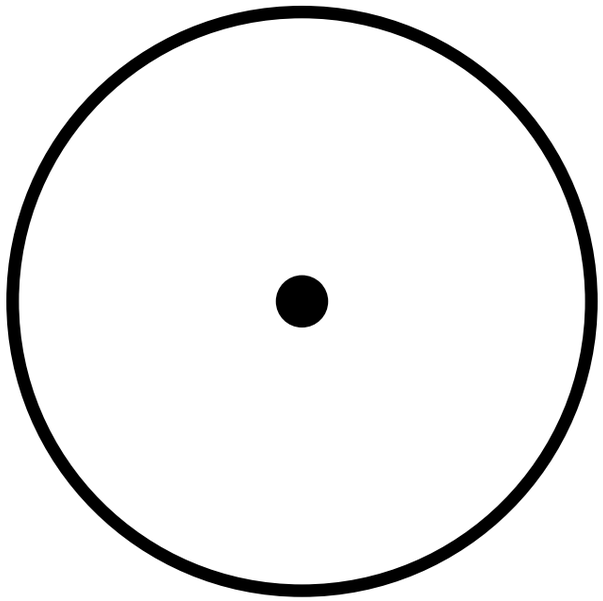

Singularities are **bad**, because there physics as we know it breaks down

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

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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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**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