Life near black holes (without math)

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presented to

IET

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What we will accomplish in this lecture

- We will develop a series of graphical methods for exploring **causality** near black holes
- We will use 2 explorers, Alice and Bob, and determine what happens during their adventures
- We will answer these questions
  - What does Bob see as Alice approaches and crosses the horizon of the hole?
  - What does Alice experience during her journey?
  - What happens when each sends messages to the other?
  - What happens if they both enter the black hole?

Alice

Bob

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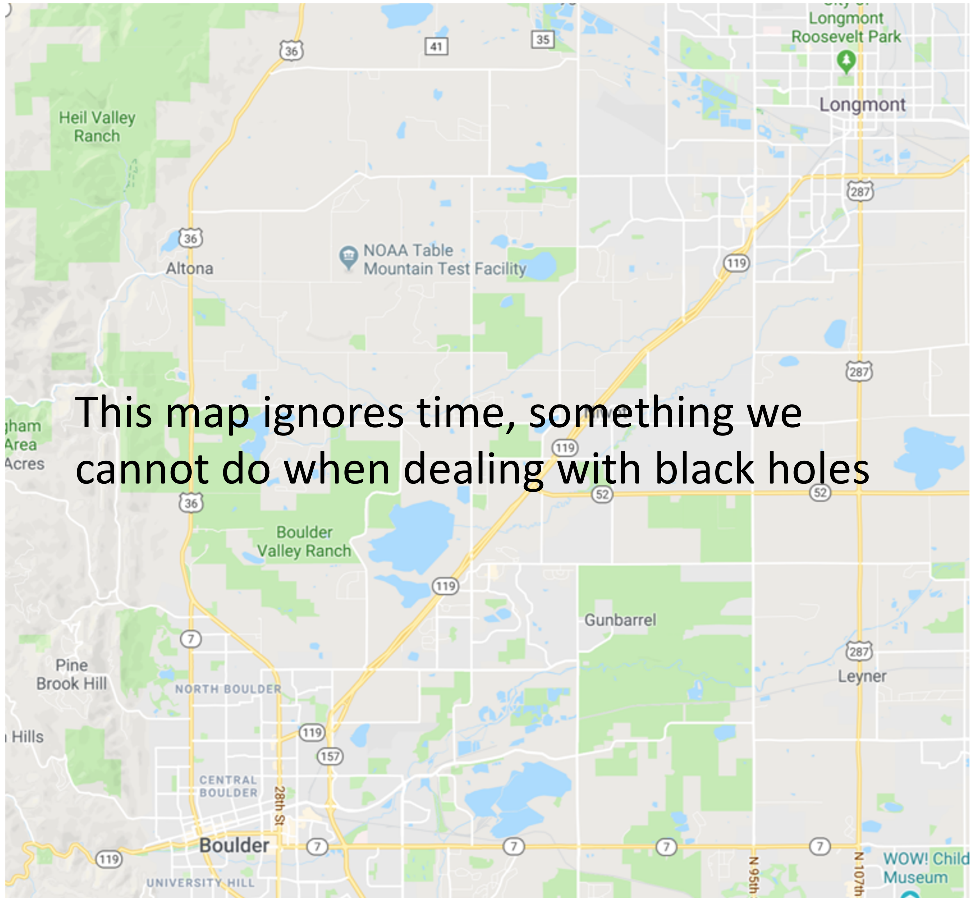
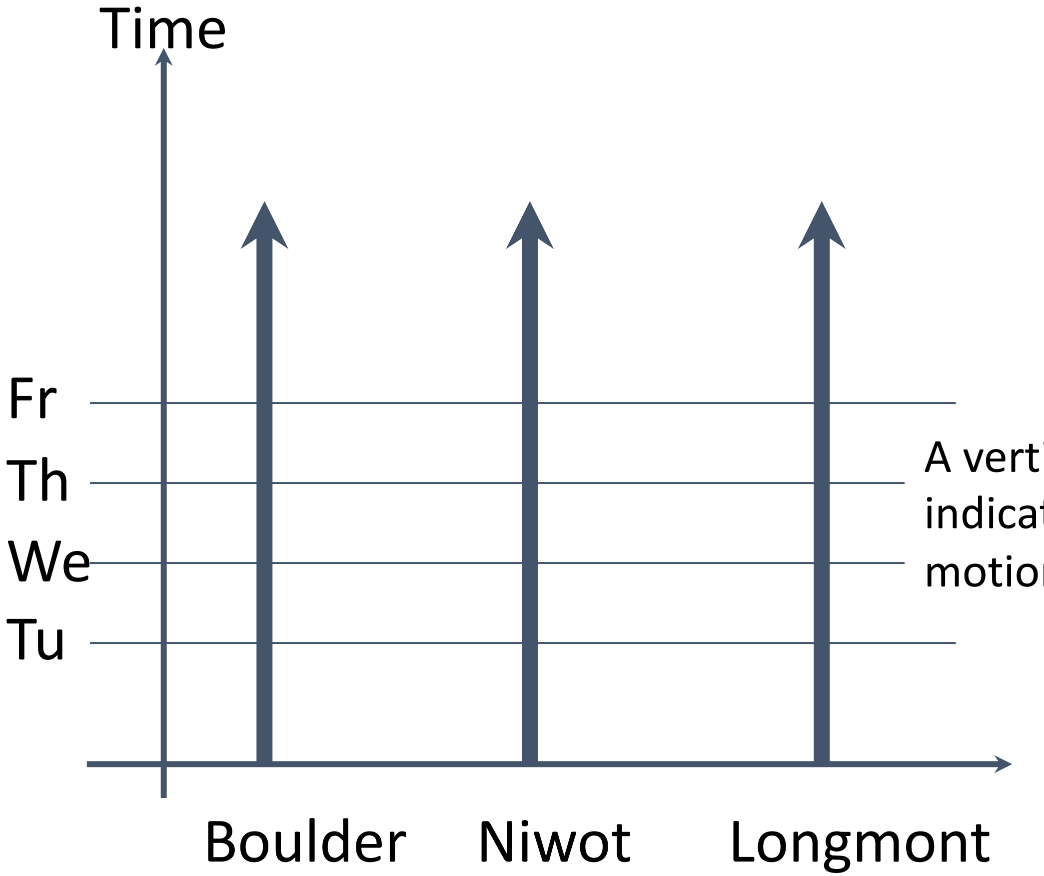
World lines provide a convenient way to start the conversation by mixing space and time



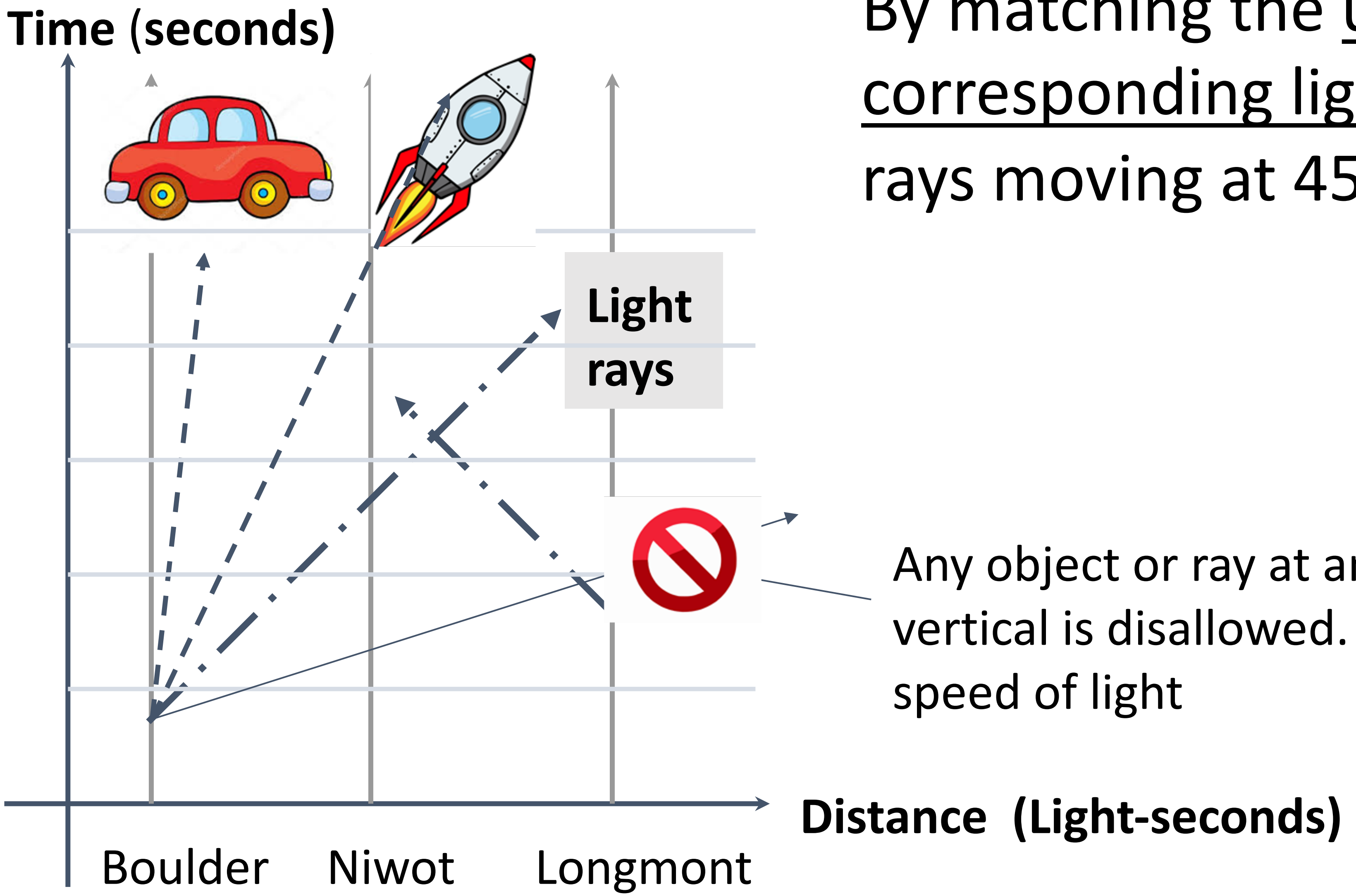
This map ignores time, something we cannot do when dealing with black holes



A vertical line indicates no motion

To add time to the map, we need a rectilinear grid of space and time. **Stationary objects appear move in this coordinate system because time advances.**

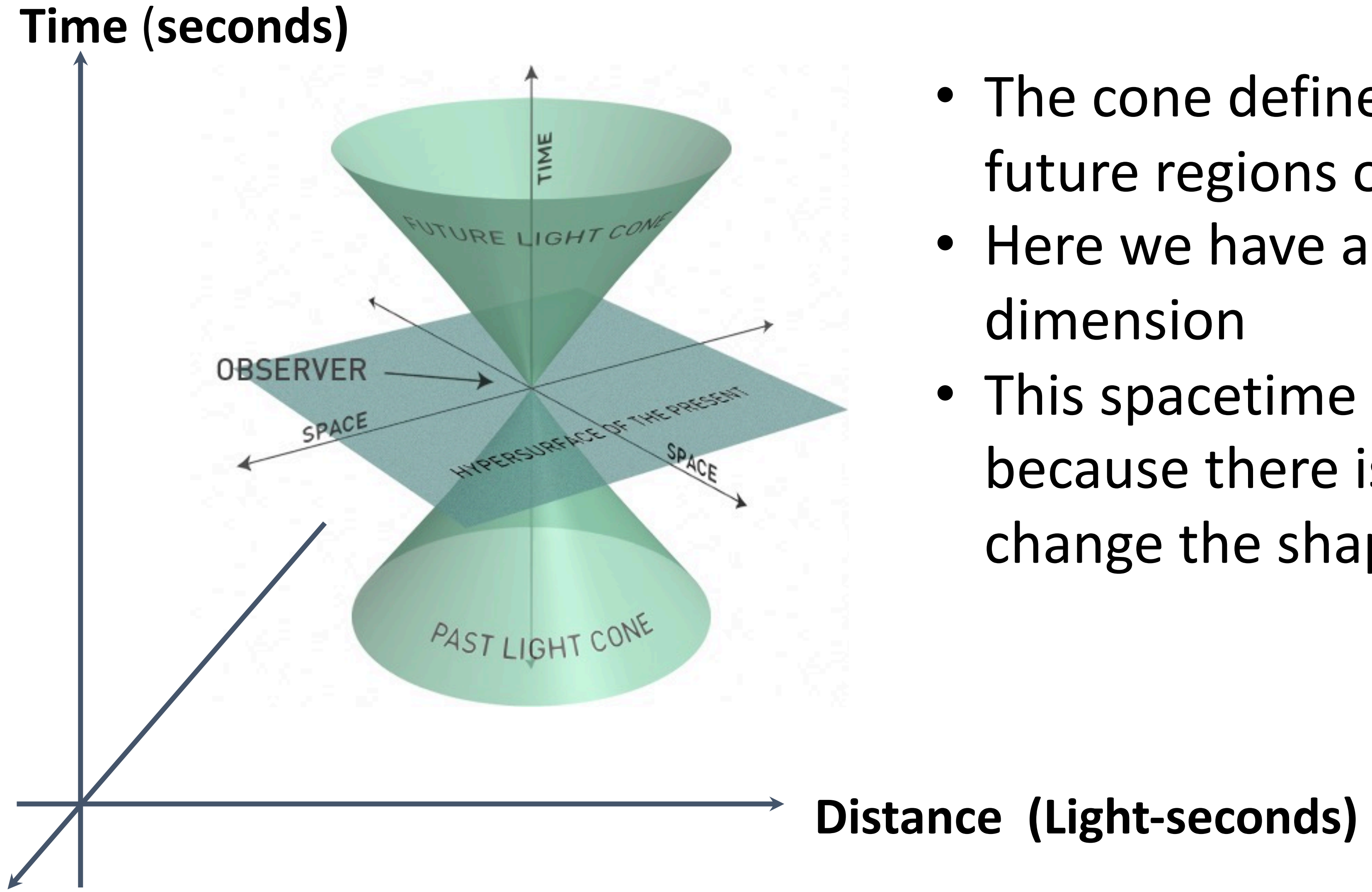
Picking the right units helps, too



By matching the <u>units in time and the corresponding light-time</u>, we get light rays moving at 45° angles

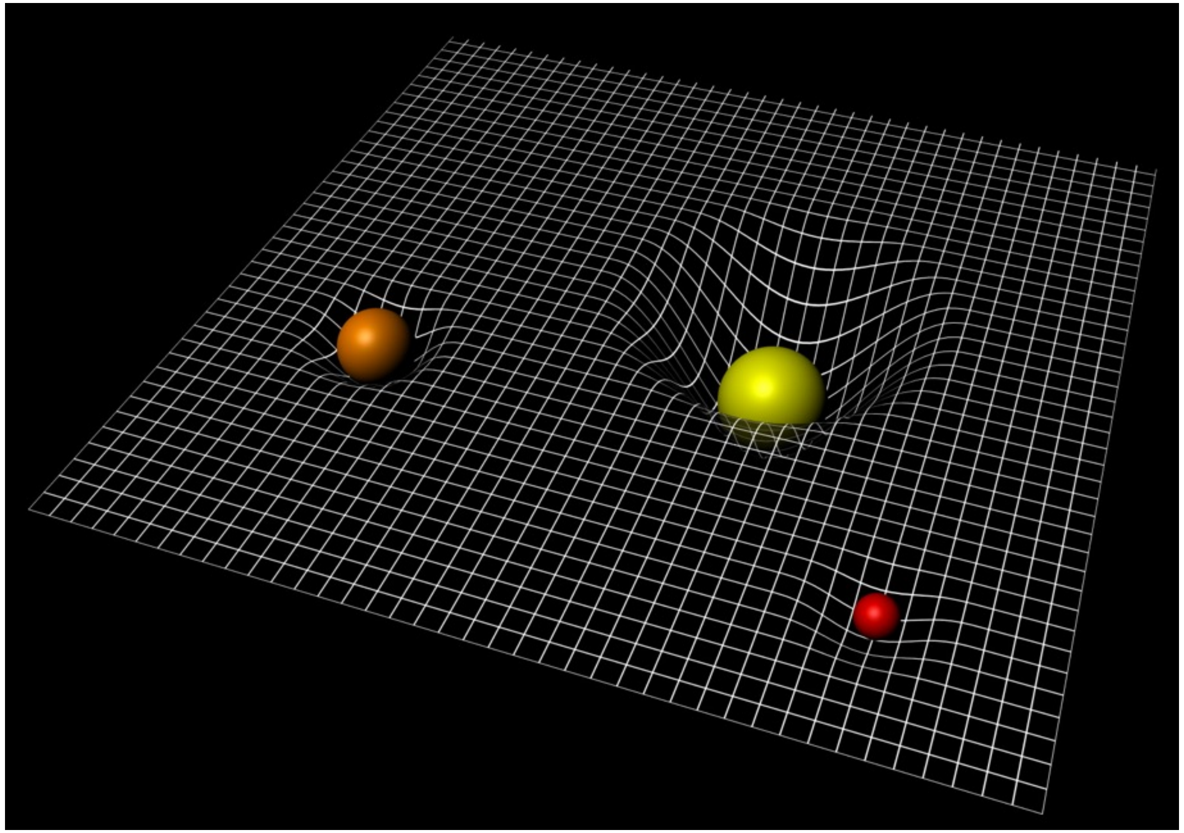
Any object or ray at an angle >45° relative to vertical is disallowed. This would exceed the speed of light

Given this new map, we can define the spacetime available to us with up to 2 dimensions of space



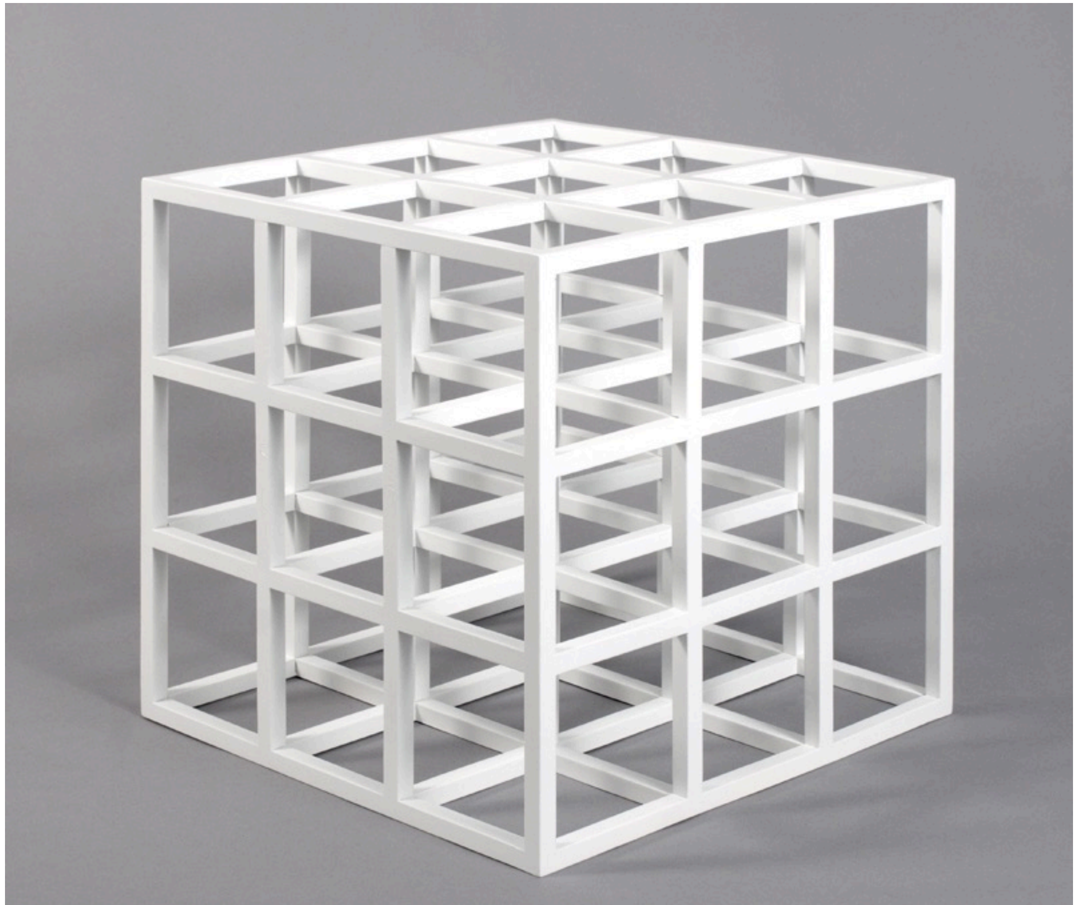
- The cone defines the only possible future regions of spacetime
- Here we have added a second spatial dimension
- This spacetime graph works fine because there is nothing around to change the shape of spacetime

We will now add matter/energy and see the effects of warping spacetime

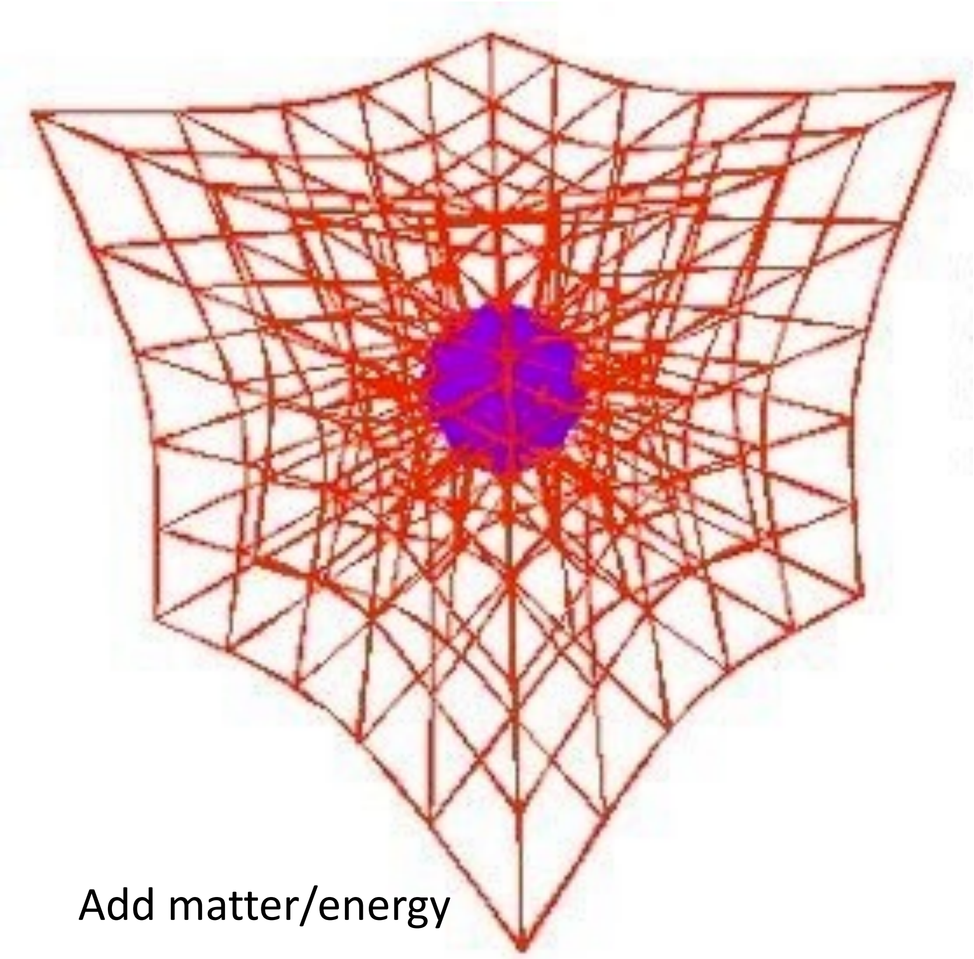


Here's a two-dimensional analog of what happens

The presence of mass or energy (they are equivalent via $E=mc^2$) changes spacetime



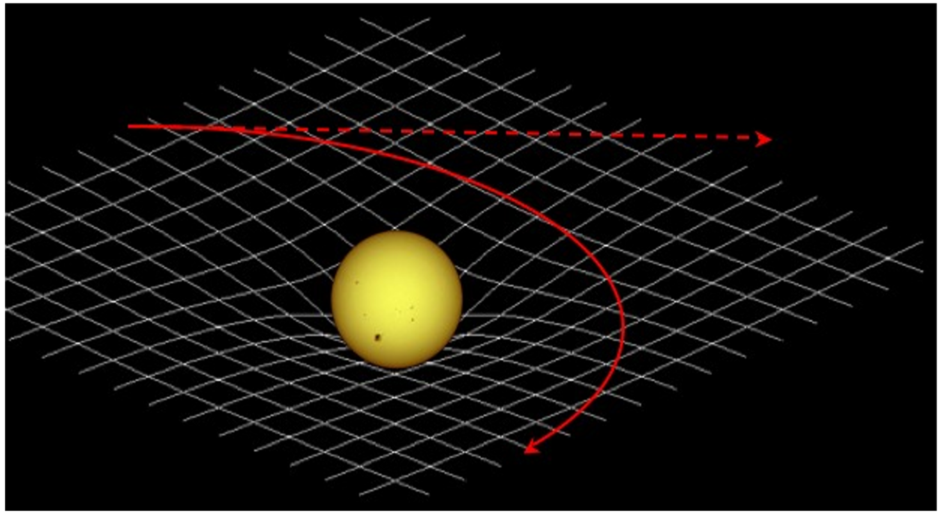
Spacetime grid with no matter/energy around



Add matter/energy

So, there is no gravity. Spacetime distortion impacts the trajectory of mass and light

- Newton's gravitational physics is really, really good
  - It provides almost all we need to send space probes through the solar system and to understand motions of the planets, galaxies and other objects.
- But, based on Einstein, we can also say that there is no such thing as gravity. There is warping of spacetime by mass/energy.
- The warping is the basis of what we call gravity.
- Wheeler says "Spacetime tells matter how to move; matter tells spacetime how to curve".



Remember that

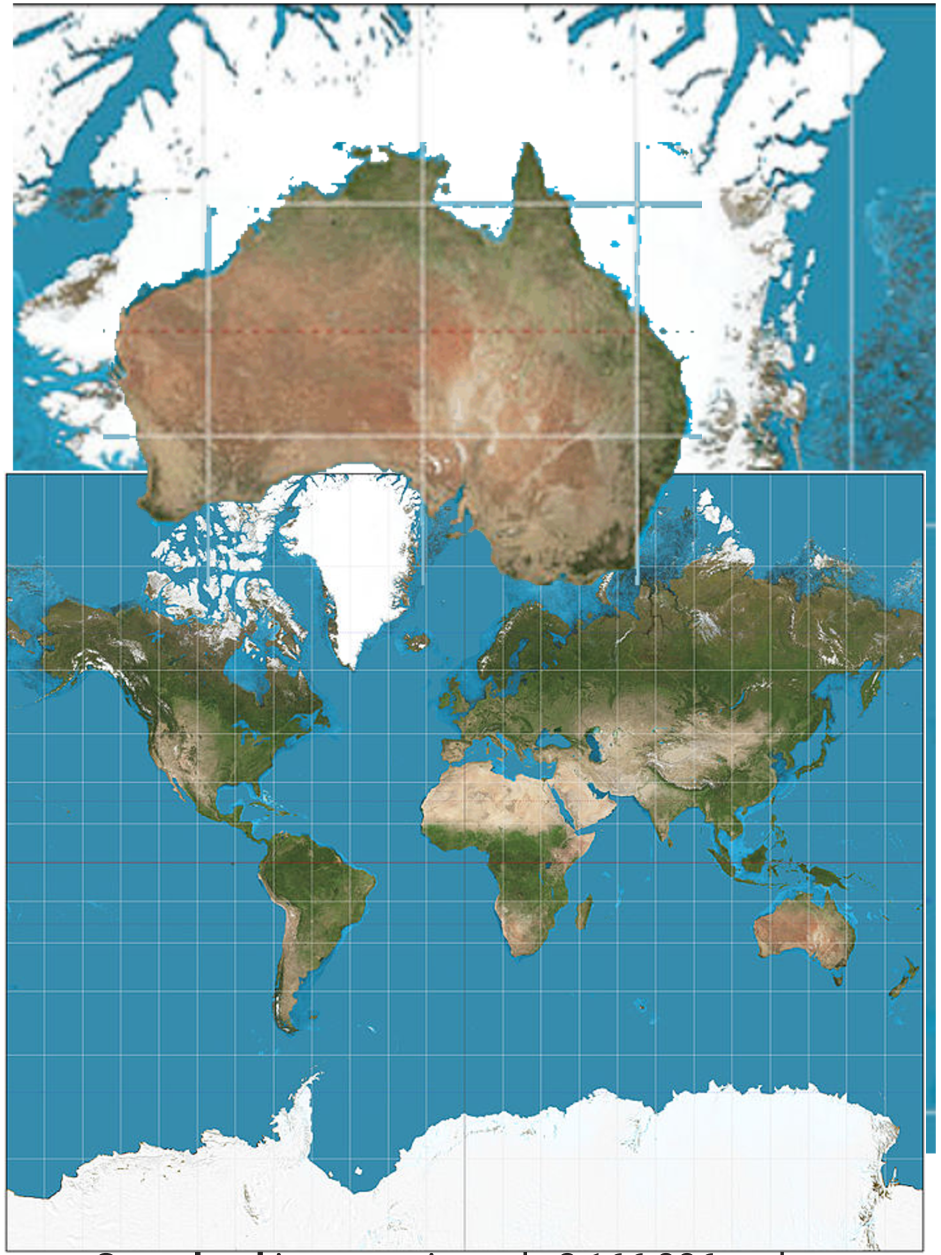
$E=mc^2$

Energy and mass are equivalent

We can expect the mesh of spacetime to take up complicate shapes due to the presence of energy.

A coordinate system that reveals these details may have to distort things

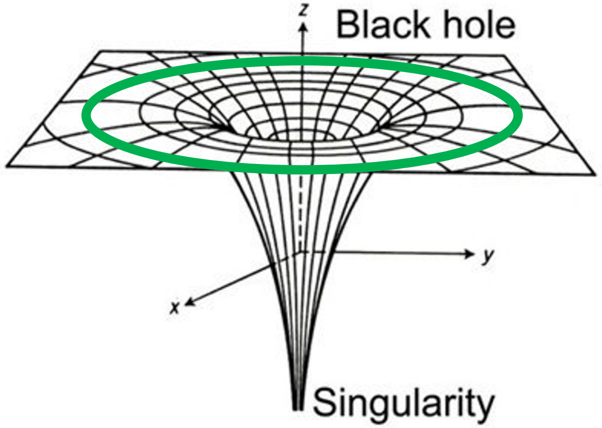
Correct



Greenland is approximately 2,166,086 sq km,
while **Australia** is approximately 7,741,220 sq km.

All the effects we will now encounter apply to all objects, but is most dramatic in the case of black holes, so we will concentrate on them

- In an extreme case, a horizon forms that separates the interior from the rest of the universe.
- At the center of the horizon is the **singularity**, a locale at which all known physics (including time) ends
- Black holes are extremely simple; they have only three properties; mass, charge and rotation
- The horizon is NOT a physical barrier, but it has profound significance



Advert for CSU Bored Scienctists Book

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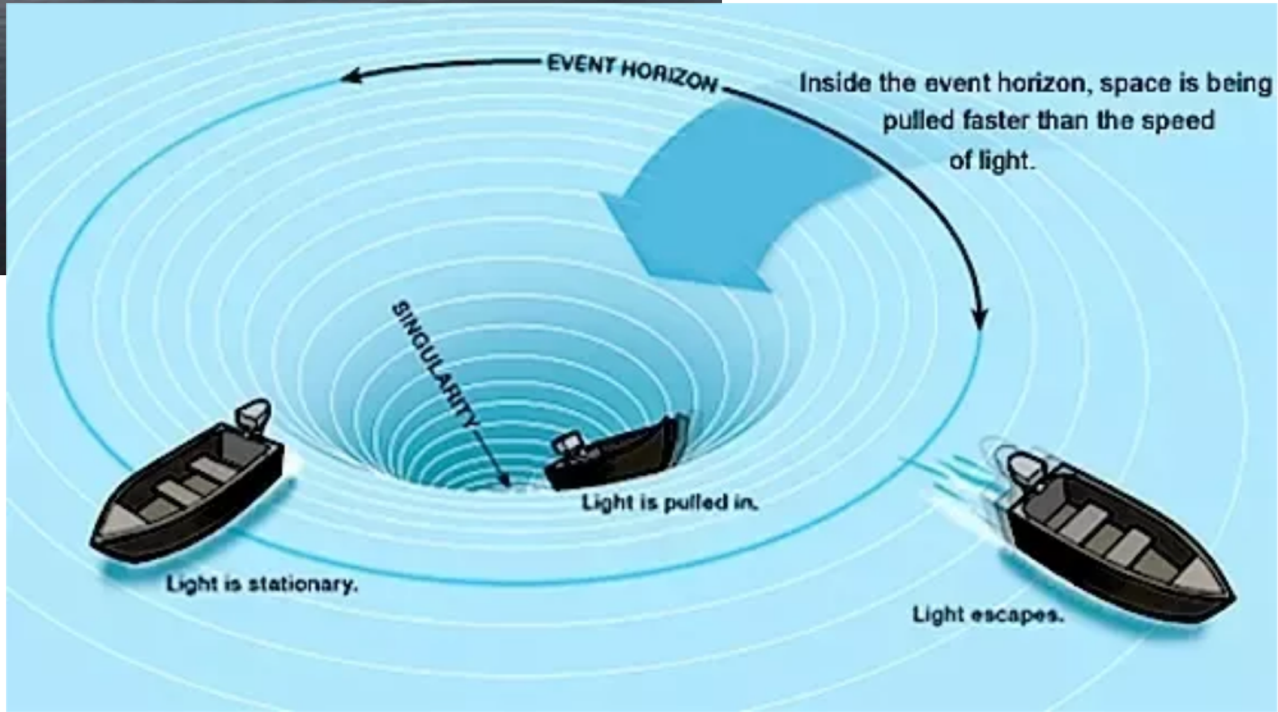
The lake metaphor helps understand the horizon

Remember that the hole is a 3 dimensional object. These depictions unavoidably suppress one of the dimensions.

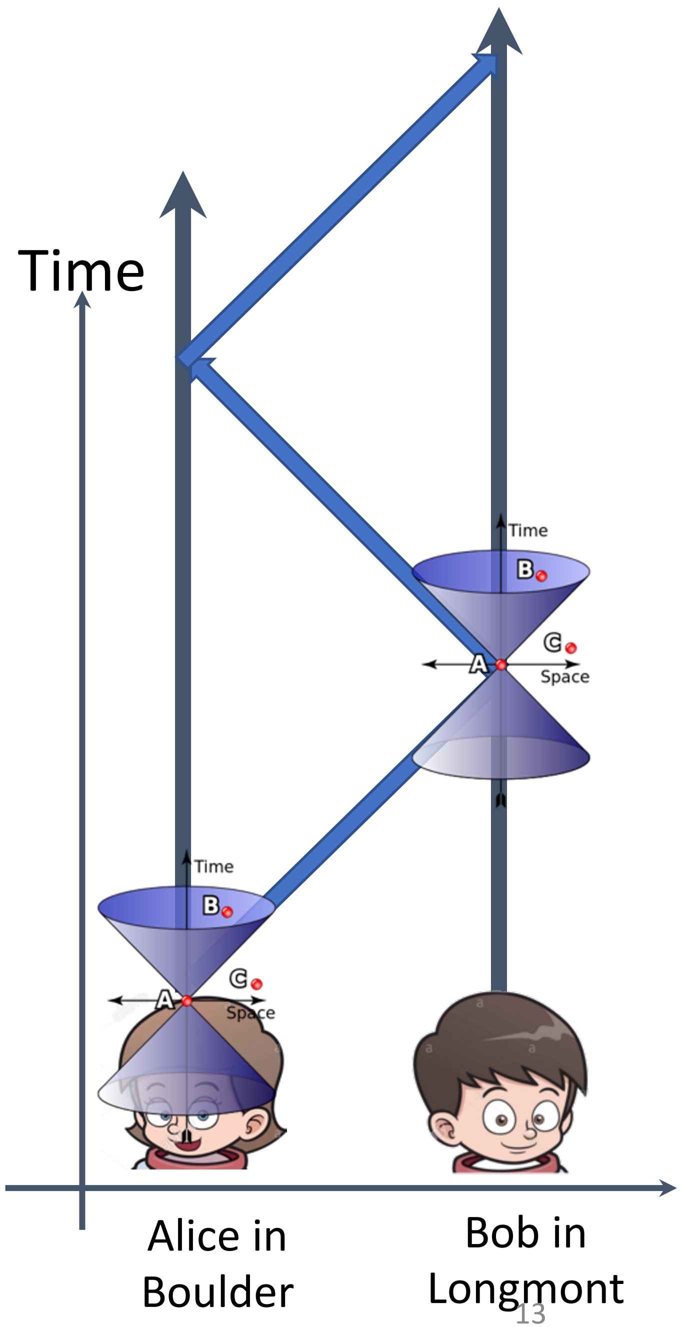


A word of warning

- What follows is challenging
- But, fear not because I will repeatedly emphasize the key points
- The method of demonstration is complicated and your retention of it will depend on my skill as a presenter, not your ability to learn
- So, stick with me and we’ll do the best we can

Communication between Alice and Bob in a massless spacetime

- Neither are moving
- Light rays move at 45 degrees
- We'll use the same type of communication scheme in the coming slides



When mass is nearby, the math is very complicated

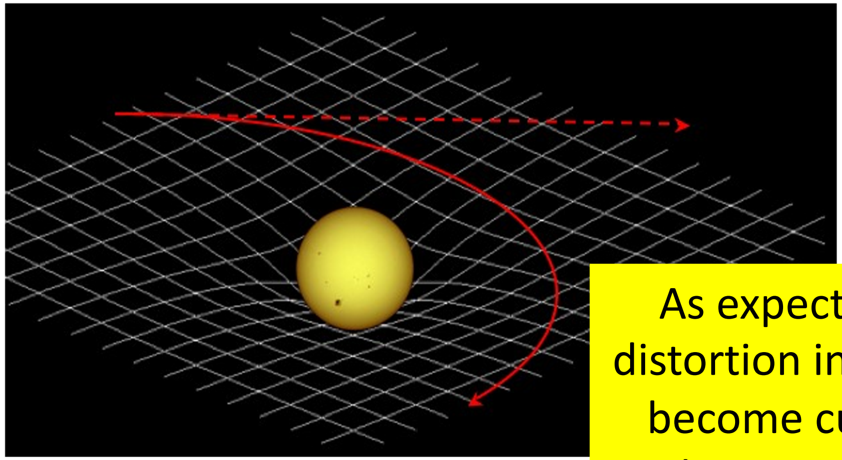
- We'd like a tool to study such a space without doing the math
    - Properly describe both flat and curved space
    - Include the horizon and singularity
    - Covers all of time and space
    - Guarantees that light rays propagate on diagonals

$$\mathbf{R}_{\mu\nu} - \frac{1}{2}\mathbf{R}\,\mathbf{g}_{\mu\nu} + \Lambda \mathbf{g}_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

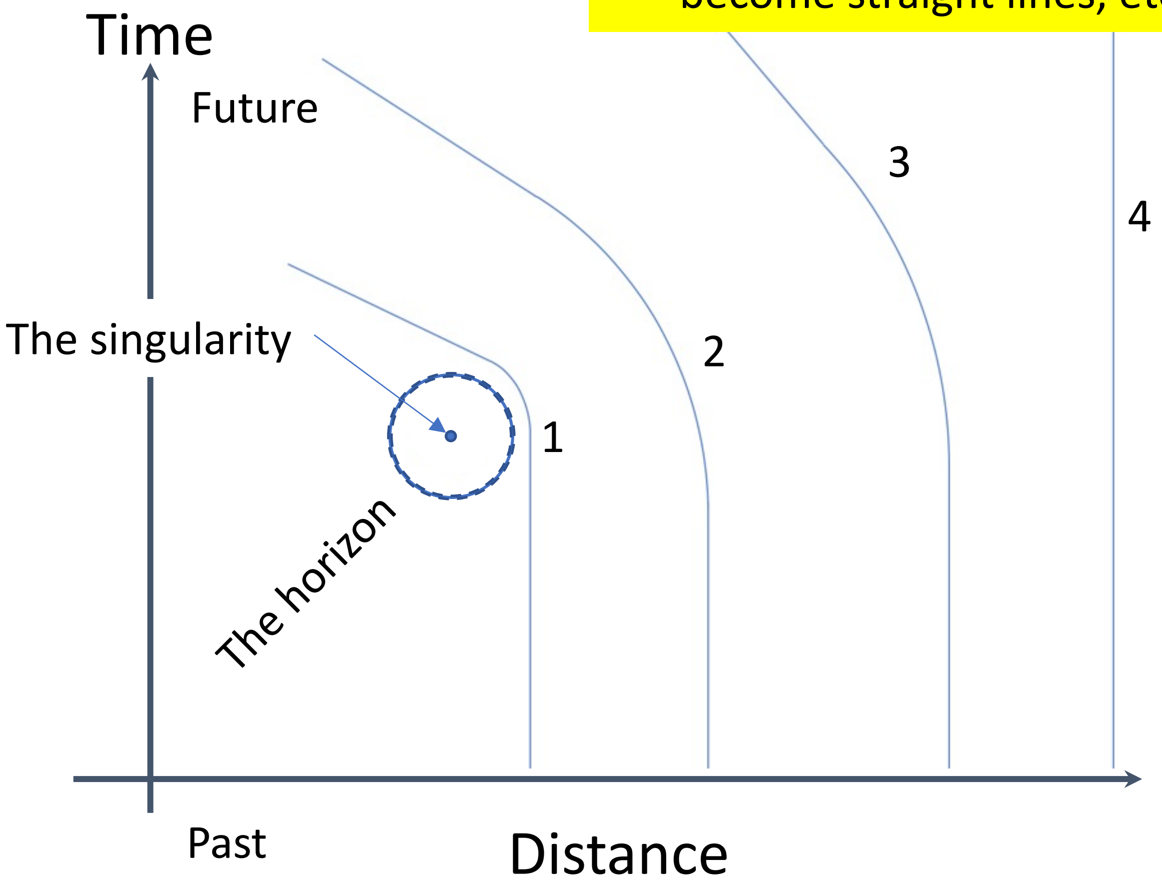
$$\begin{aligned}
&W\left[\frac{\xi}{\alpha}\left(\frac{\partial f}{\partial t} - \beta^r \frac{\partial f}{\partial r}\right) + \frac{\nu}{\phi^2}\frac{\partial f}{\partial r}\right] - \frac{\varepsilon W^3}{r\alpha\phi^3}\frac{\partial f}{\partial \varepsilon} \\
&\quad \times \left\{\beta^r \phi^3\left(-\psi - r\mu \frac{\partial v_r}{\partial r}\right) + v_r^2 \phi\left[\beta^r \phi\left(2r\frac{\partial \phi}{\partial r} - \psi\phi\right)\right.\right. \\
&\quad \left. + r\left(-\mu\frac{\partial \alpha}{\partial r} + \mu^2\phi^2\frac{\partial \beta^r}{\partial r} - \frac{\partial \phi^2}{\partial t}\right)\right] \\
&\quad + v_r^3\left[r\mu\phi\left(-\mu\frac{\partial \alpha}{\partial r} + \frac{\partial \beta^r \phi^2}{\partial r} - \frac{\partial \phi^2}{\partial t}\right) - \psi\frac{\alpha}{\phi}\frac{\partial r\phi^2}{\partial r}\right] \\
&\quad + \phi\left[r\mu\left(\mu\alpha\frac{\partial v_r}{\partial r} + \frac{\partial \alpha}{\partial r} + \phi^2\left(-\mu\frac{\partial \beta^r}{\partial r} + \frac{\partial v_r}{\partial t}\right)\right)\right. \\
&\quad \left. + r\frac{\partial \phi^2}{\partial t} - r\beta^r\frac{\partial \phi^2}{\partial r}\right] + v_r\alpha\left[\phi\left(\psi + r\mu\frac{\partial v_r}{\partial r}\right)\right. \\
&\quad \left.\left. + 2r\psi\frac{\partial \phi}{\partial r} + \phi^2\left(\mu\frac{\partial v_r}{\partial t} - \frac{\partial \beta^r}{\partial r}\right) + \frac{\partial \phi^2}{\partial t}\right]\right\} \\
&\quad + \frac{W^3(1-\mu^2)}{r\alpha\phi^3}\frac{\partial f}{\partial \mu}\left\{\alpha\left[\phi\left(\frac{\xi}{W^2} - r\nu\frac{\partial v_r}{\partial r}\right) + 2r\frac{\xi}{W^2}\frac{\partial \phi}{\partial r}\right]\right. \\
&\quad + \phi\left[\beta\phi^2\left(r\xi\frac{\partial v_r}{\partial r} - \frac{\nu}{W^2}\right) - \frac{r}{W^2}\left(\xi\frac{\partial \alpha}{\partial r} - \nu\phi^2\frac{\partial \beta^r}{\partial r}\right)\right. \\
&\quad \left.\left. - r\xi\phi^2\frac{\partial v_r}{\partial t}\right]\right\} = \mathfrak{C}[f], \qquad (26)
\end{aligned}$$

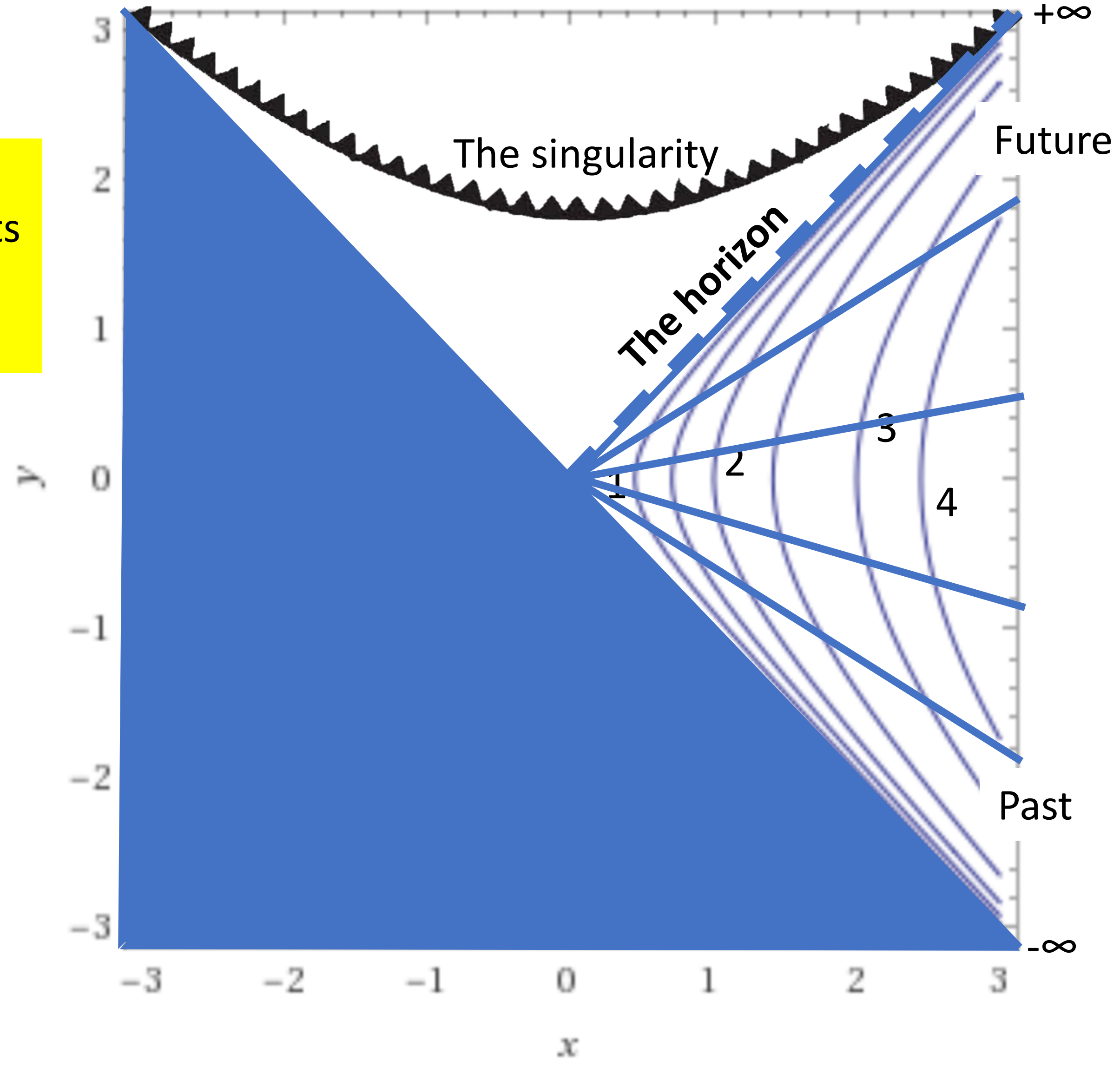
25 minutes to go

The Kruskal diagram helps visualize everything with no math



As expected, there is a lot of distortion in this mapping; points become curved lines, spheres become straight lines, etc.

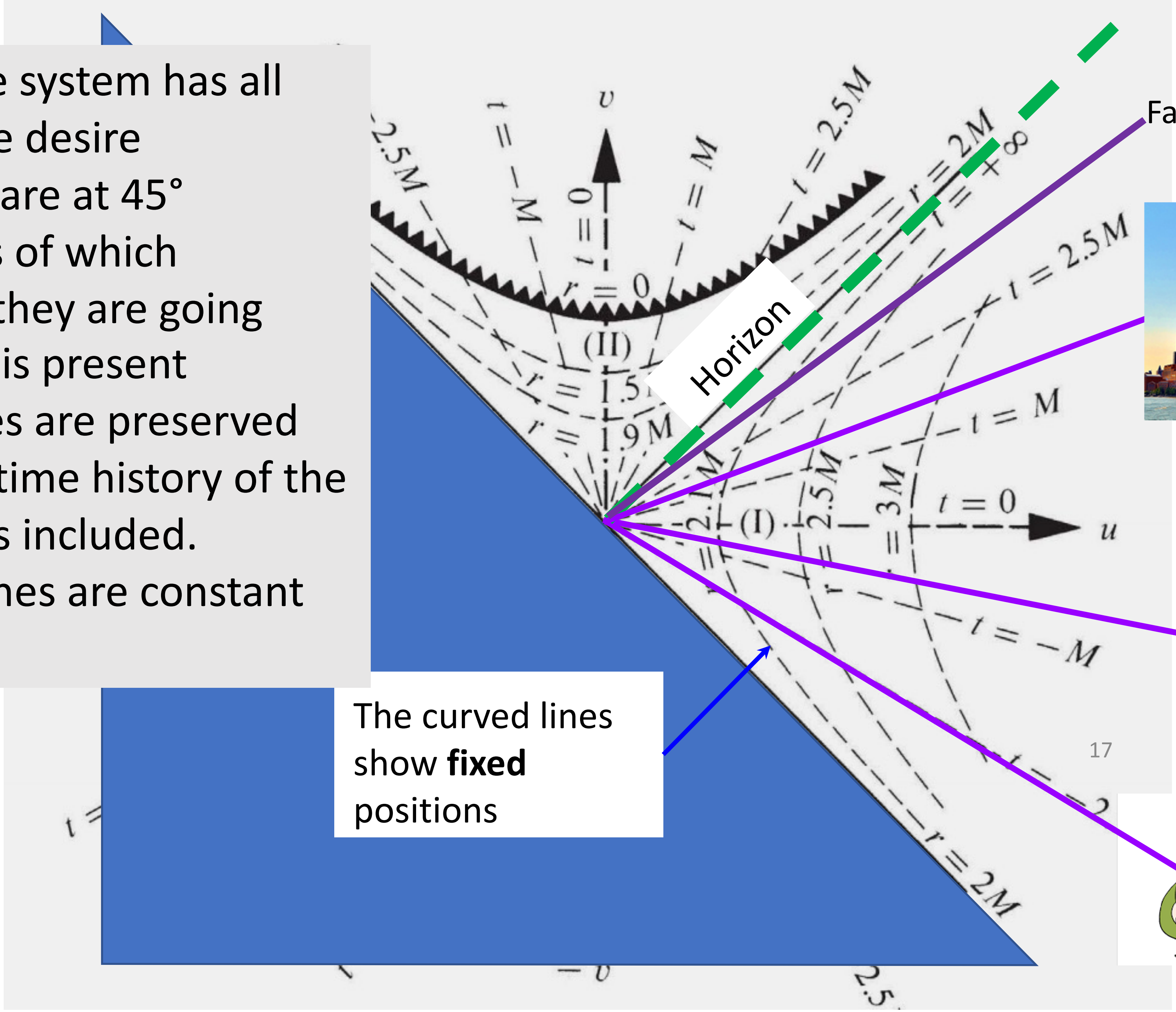


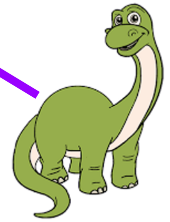


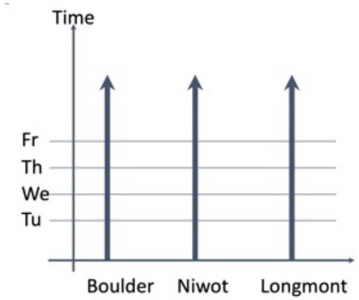
The curved lines show constant position

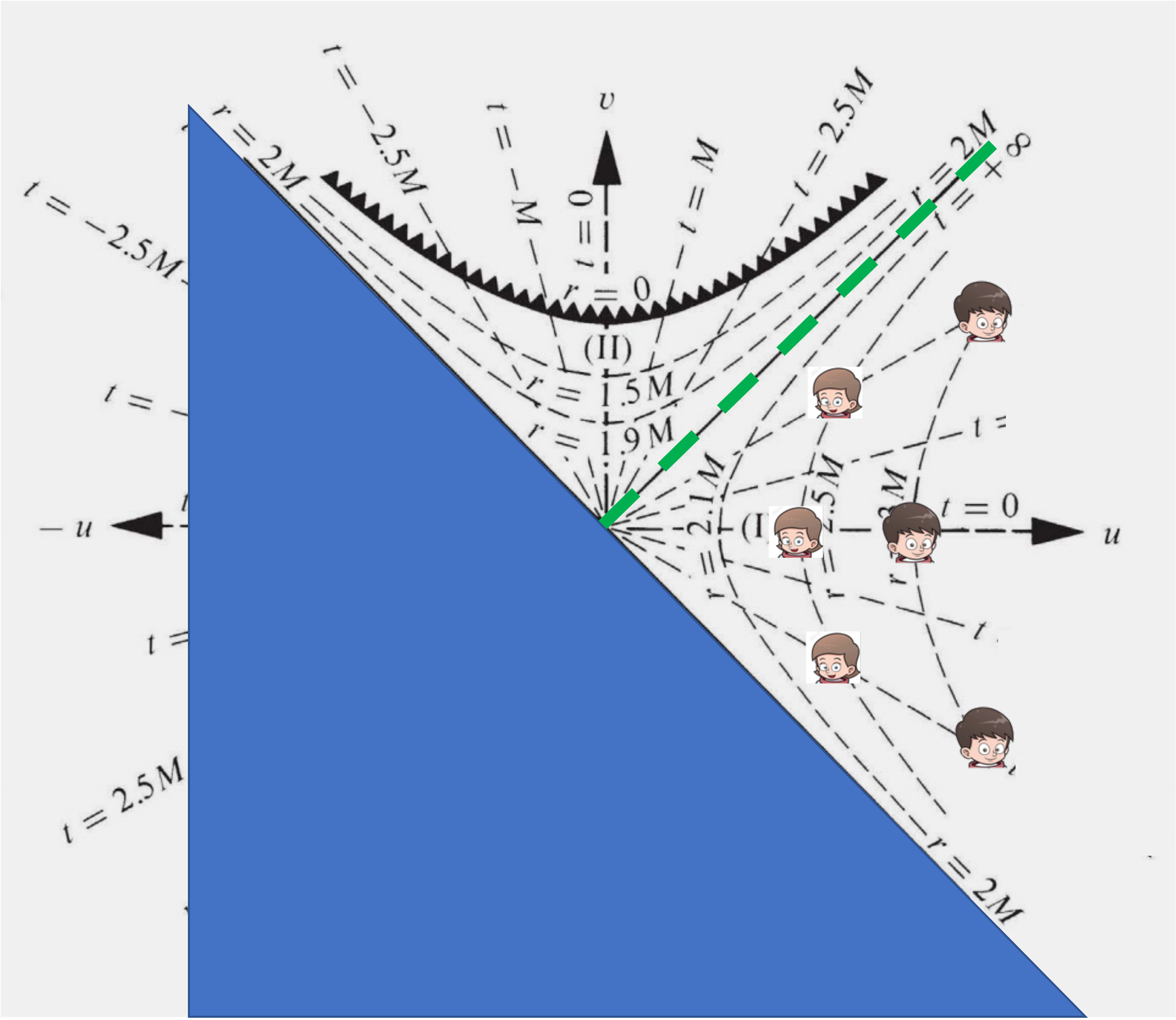
This coordinate system has all the features we desire

- Light rays are at 45° regardless of which direction they are going
- A horizon is present
- Light cones are preserved
- All of the time history of the universe is included.
- Straight lines are constant time

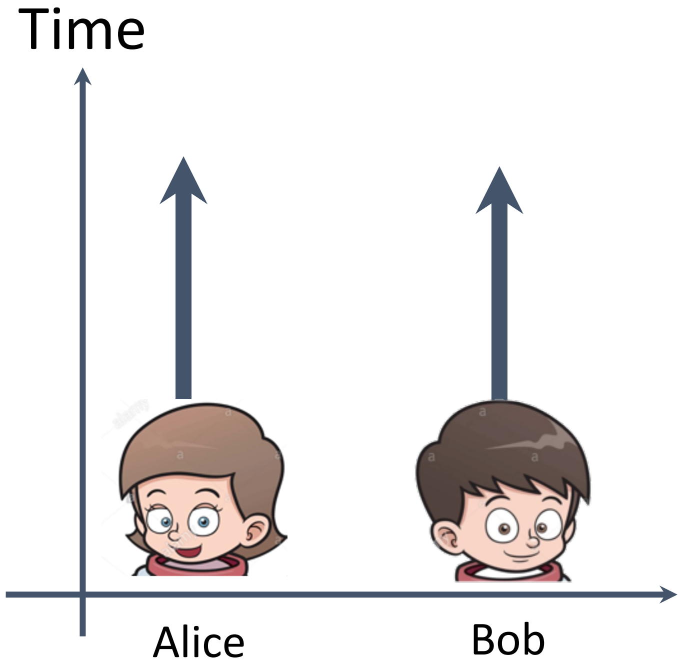








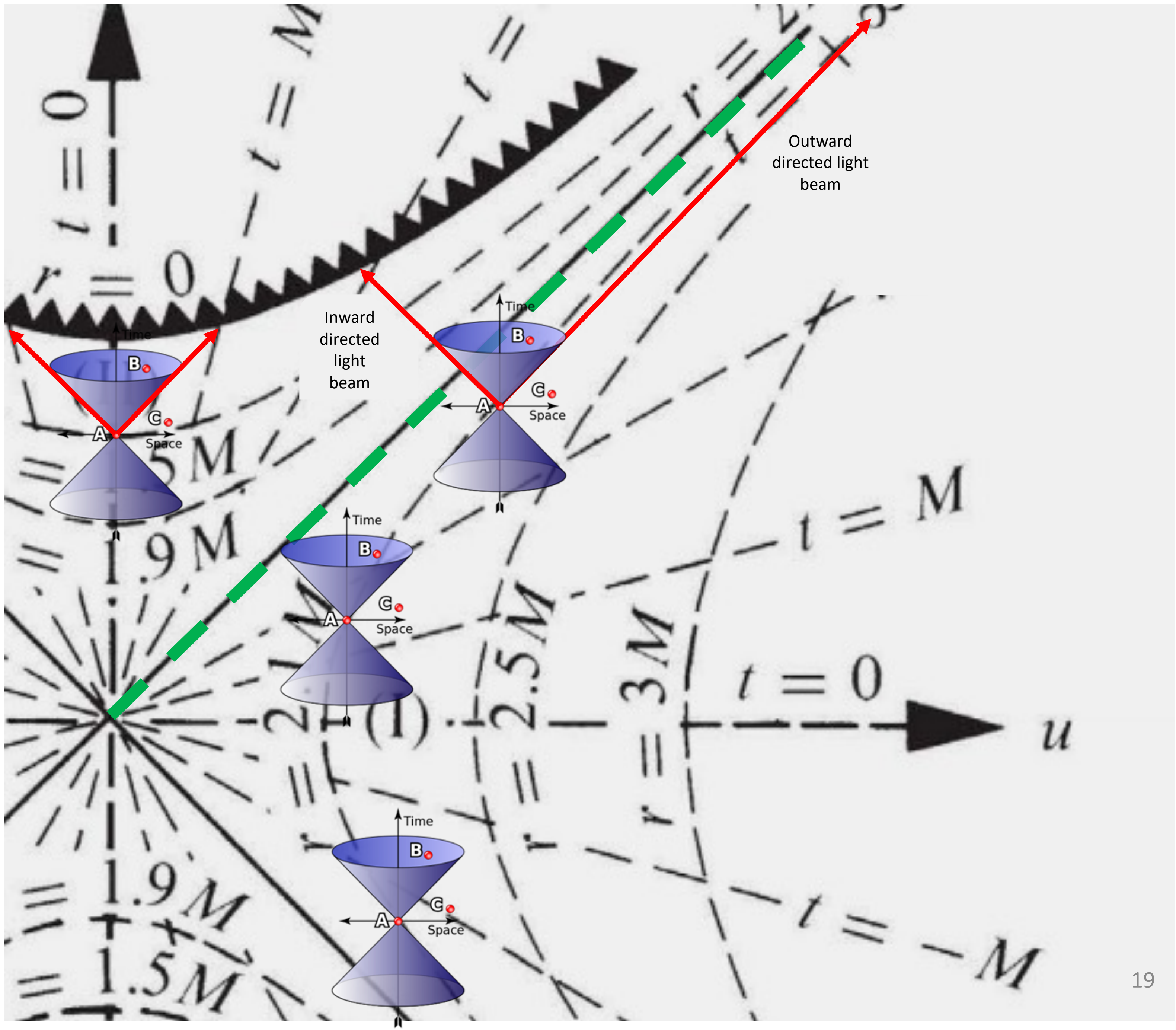
Here’s what happens if no one moves



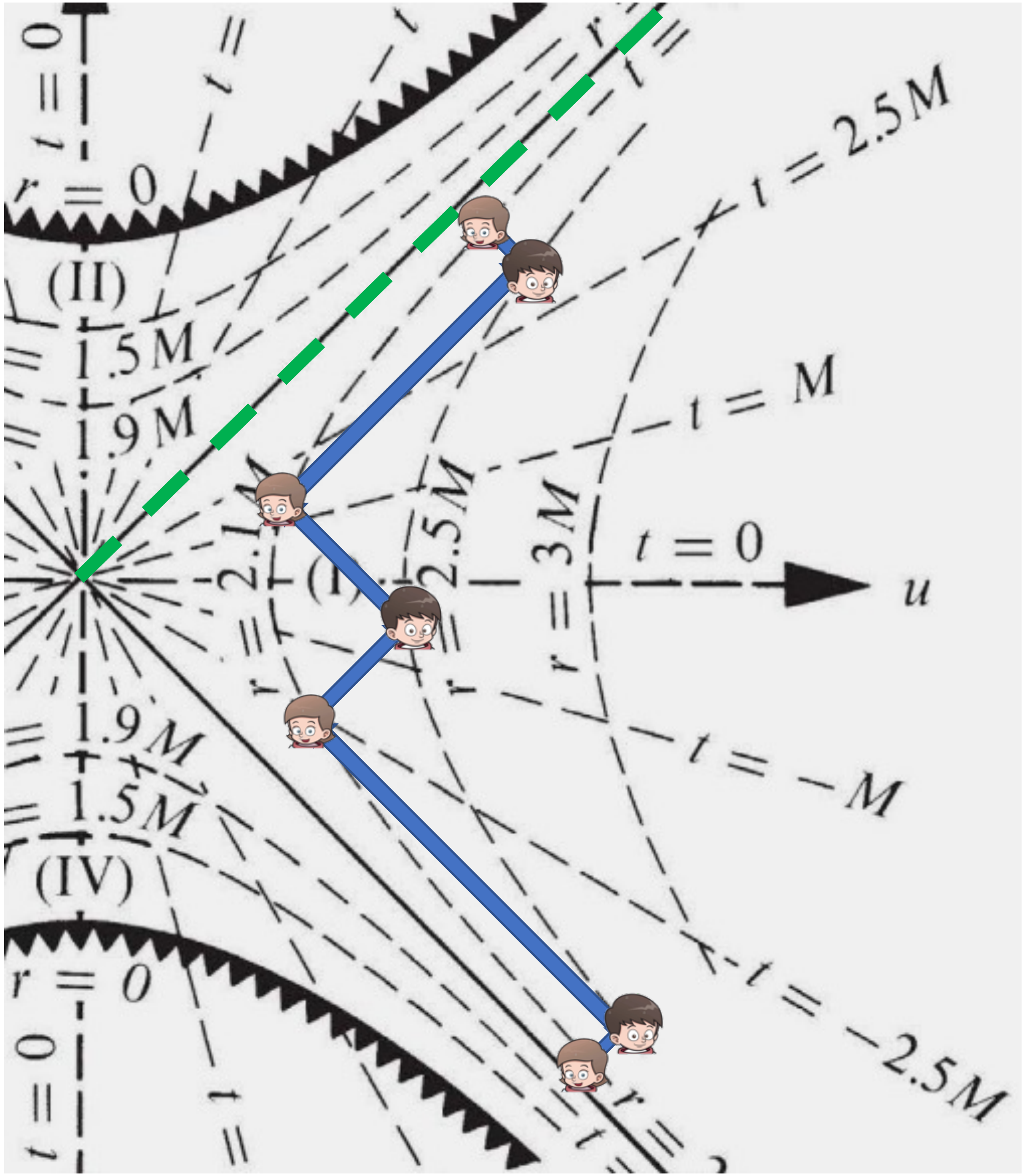
What does the map say about spacetime with a horizon?

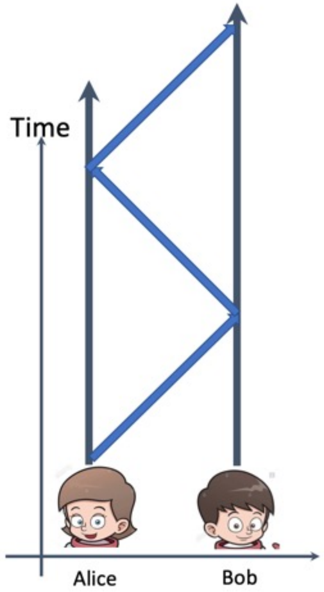
- In every case, your past or future is limited to the blue light cones
- Inside the horizon, your futures are limited to the singularity

The thin red lines show that your choices always include diving into the hole or staying away but if you are inside, all your choices lead to the singularity

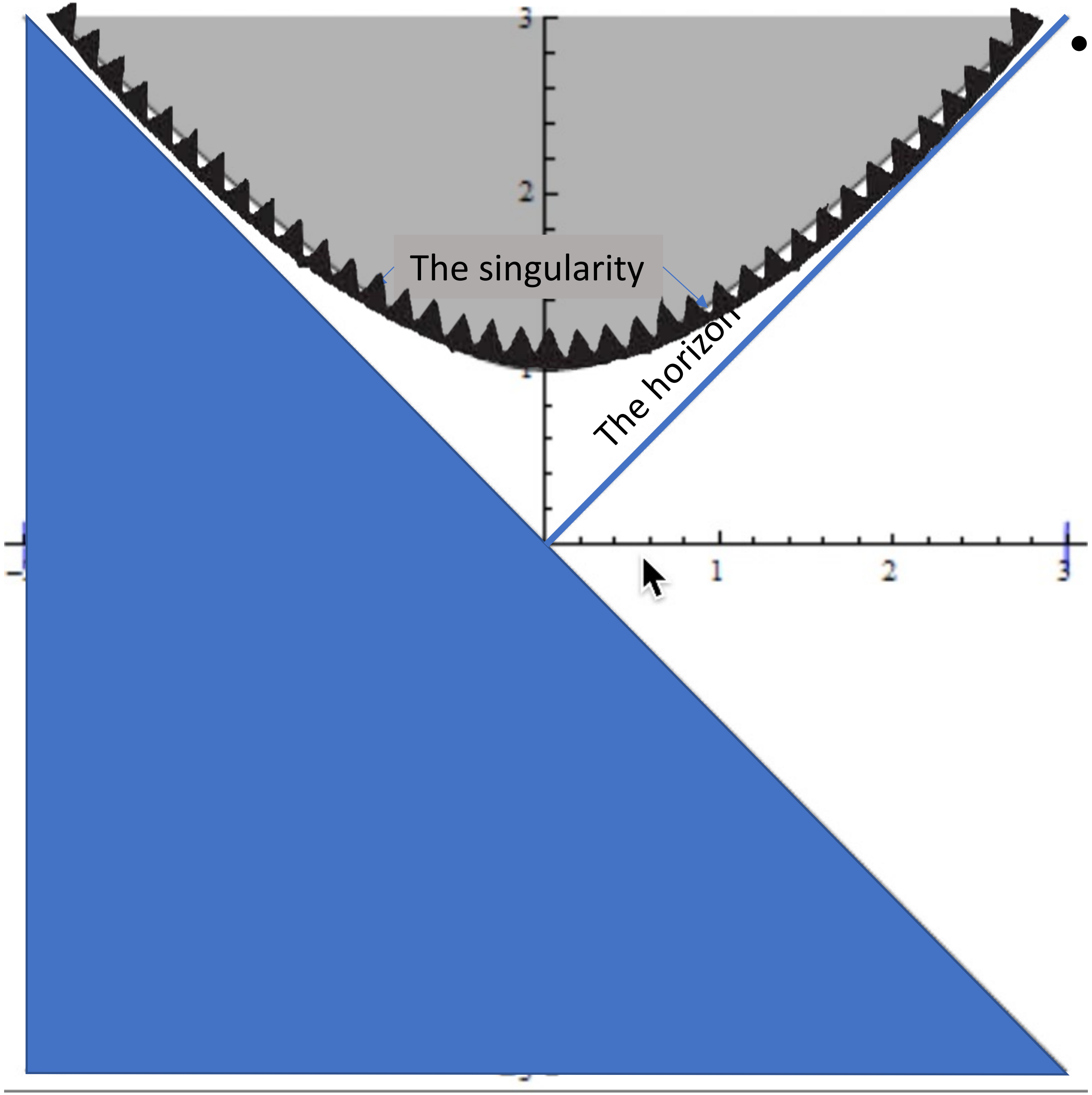


- As before, we make communication using light rays
- Even though Alice and Bob are not moving, the lines change in length because of the coordinate system we have chosen





Far from the hole light rays will like they do in flat space

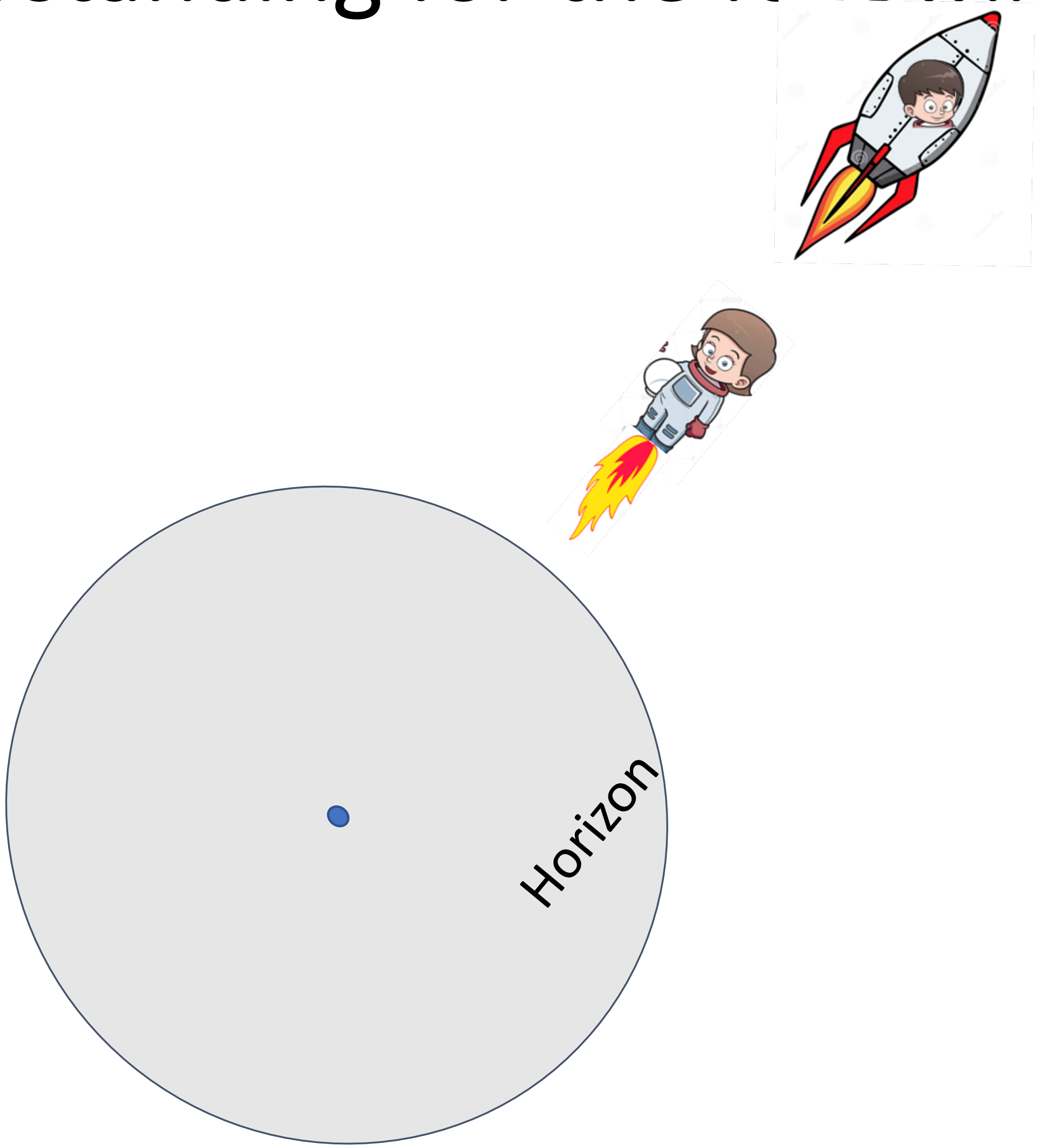


- Approaching the hole means you cross the horizon and end up at the singularity
  - **The spatial coordinate changes to a time coordinate**

Inside the horizon, your future is not a time, **it's a place** (!) and that place is the singularity

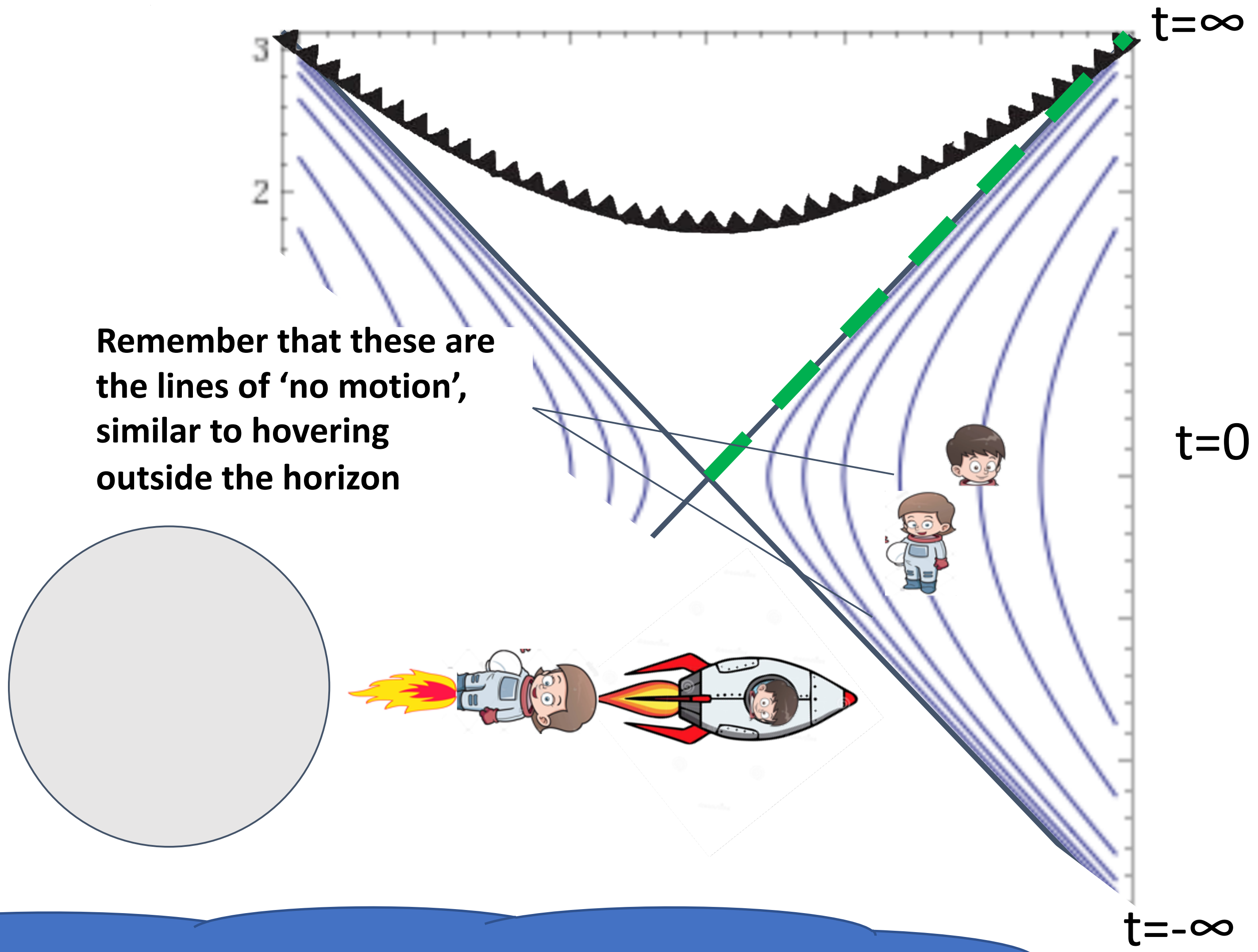
Let’s extend our understanding for the following situation

- Consider astronauts Alice and Bob **hovering** or **orbiting** near a black hole
- If either shuts off their rocket, they will fall into the hole
- All the experiments we will explore involve RADIAL motion of Bob and Alice but the same results apply to an orbiting astronaut



Now we use the Kruskal diagram for the two astronauts

- Let Bob and Alice communicate by light beams
- At first, both Bob and Alice keep firing their rockets to stay above the horizon and move along the curves at right.
- Later, Alice shuts off her rocket so she can enter along the path shown by the arrow
- We can use the graph to answer these and other questions
  - What does Bob see as Alice approaches and crosses the horizon?
  - What does Alice experience on her journey?
  - How long can Alice's send messages to Bob? How are the messages impacted by distortion of the mesh?
  - What is her future?



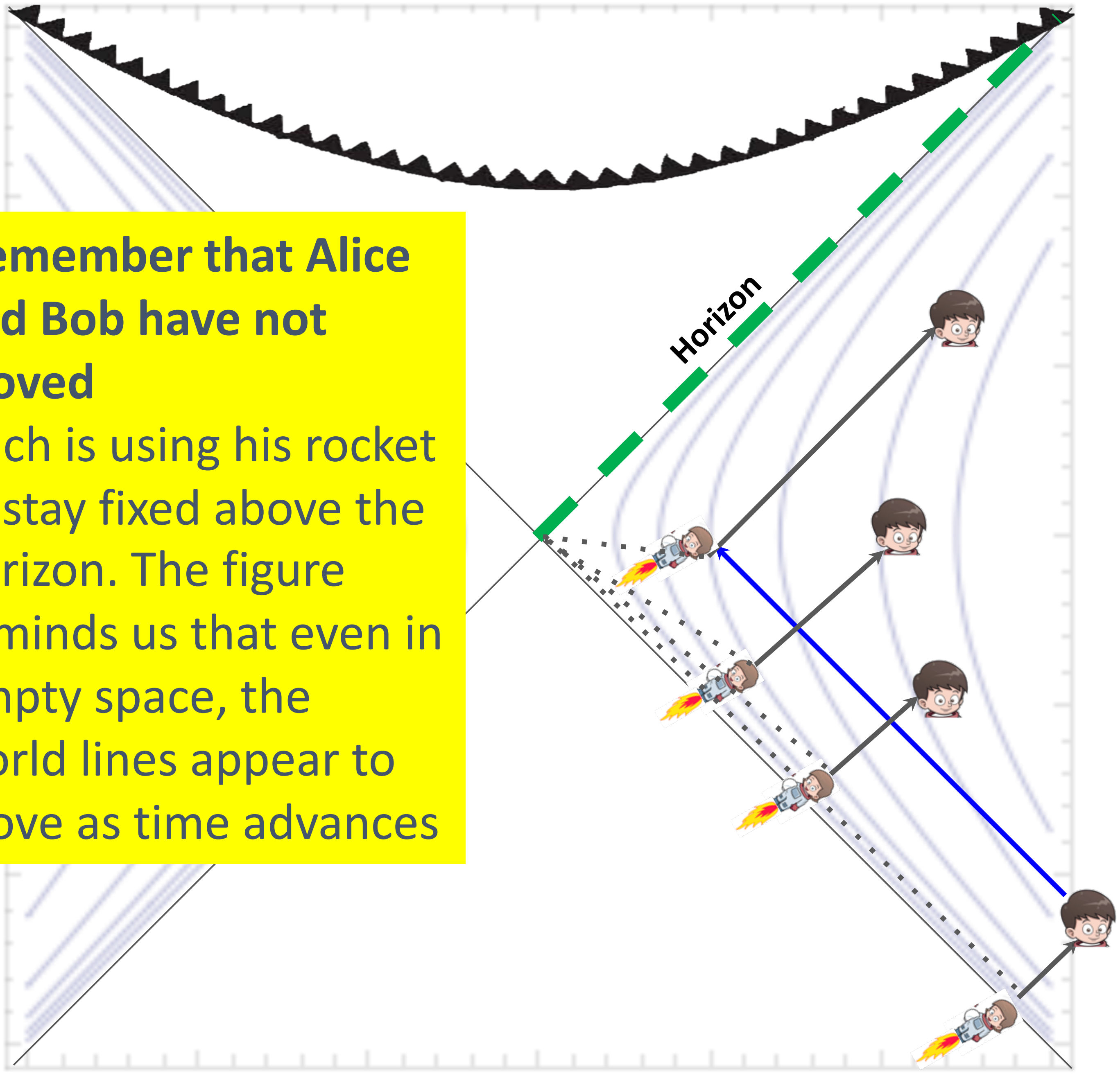
I can give a future lecture on the environment inside and outside the horizon that would be hazards near a real black hole

- Before starting the experiments, Alice and Bob send messages back and forth with no trouble
- To avoid confusion, only one of Bob's messages is shown (in blue)

Notes

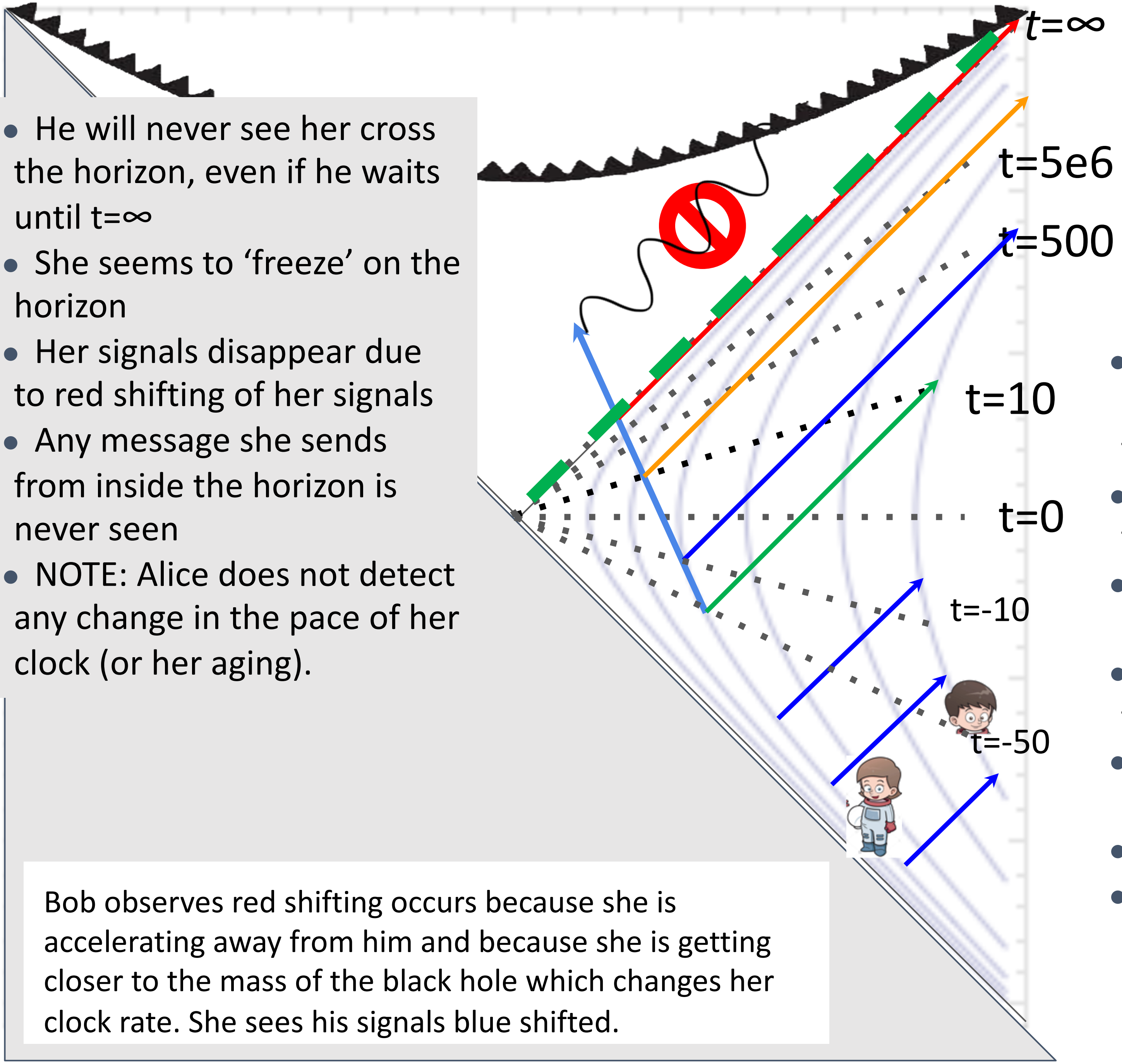
-Due to the non-linearity of the coordinate system, the arrows depicting communication are different lengths even though **the distance between Alice and Bob is not changing**

-The dotted lines show the advance of time in this coordinate system



- **Remember that Alice and Bob have not moved**
- Each is using his rocket to stay fixed above the horizon. The figure reminds us that even in empty space, the world lines appear to move as time advances

- **Experiment 1-Alice decides to cross the horizon**
- **They agree that she will send regular messages. They form a type of clock.**



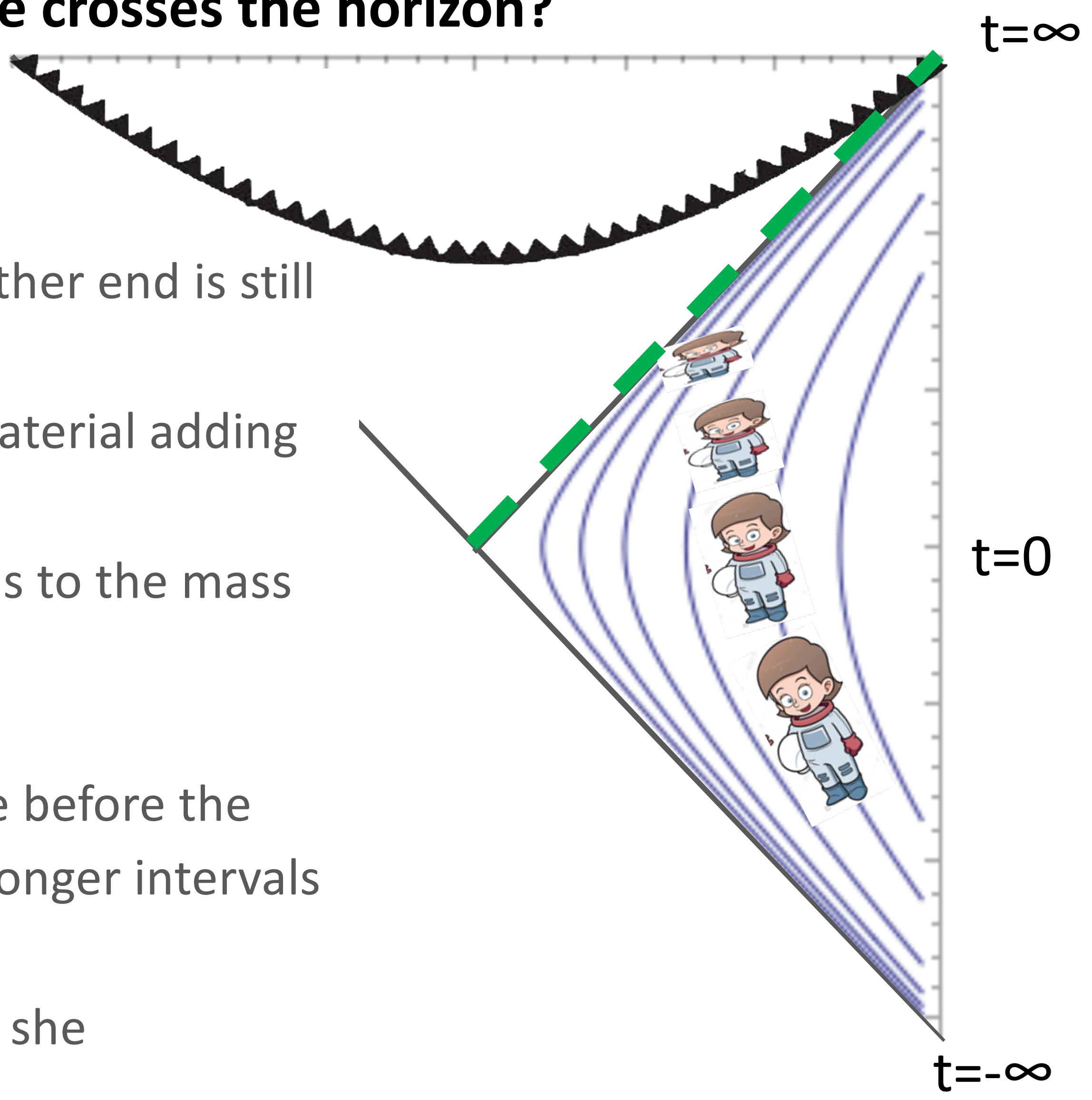
- He will never see her cross the horizon, even if he waits until t=∞
- She seems to 'freeze' on the horizon
- Her signals disappear due to red shifting of her signals
- Any message she sends from inside the horizon is never seen
- NOTE: Alice does not detect any change in the pace of her clock (or her aging).

Bob observes red shifting occurs because she is accelerating away from him and because she is getting closer to the mass of the black hole which changes her clock rate. She sees his signals blue shifted.

- When Alice shuts off her rocket (t=-50), she sends a message to Bob, which he receives at t=+10 (green line). 60 second time delay
- Her message at -10 arrives at +500. 510 second time delay
- Her message at t=10 gets to him much later (orange line). Years of time delay
- A message she sends at the instant of crossing the horizon is never received (red line)
- Clearly, the messages arrive at larger and larger intervals, as seen by Bob.
- Her clock seems to be slowing
- And no message she sends after crossing the horizon ever gets to Bob

Experiment 2 What does Bob observe as Alice crosses the horizon?

- Bob sees her 'flatten' out on the horizon
    - Imagine a long stick entering the horizon
    - The first part appears to freeze while the other end is still moving
- Anyone staying on the 'outside' sees all of the material adding to the hole fixed on the surface
- Clearly, the material crosses the horizon and adds to the mass of the hole but this is not what Bob sees.
- He sees her clock slow down
    - Bob and Alice agreed to a transmission rate before the experiment, but he will detect longer and longer intervals between her transmission
- He will see red shifting in her transmissions until she disappears



Remember that in spite of the images at right, Alice is moving radially

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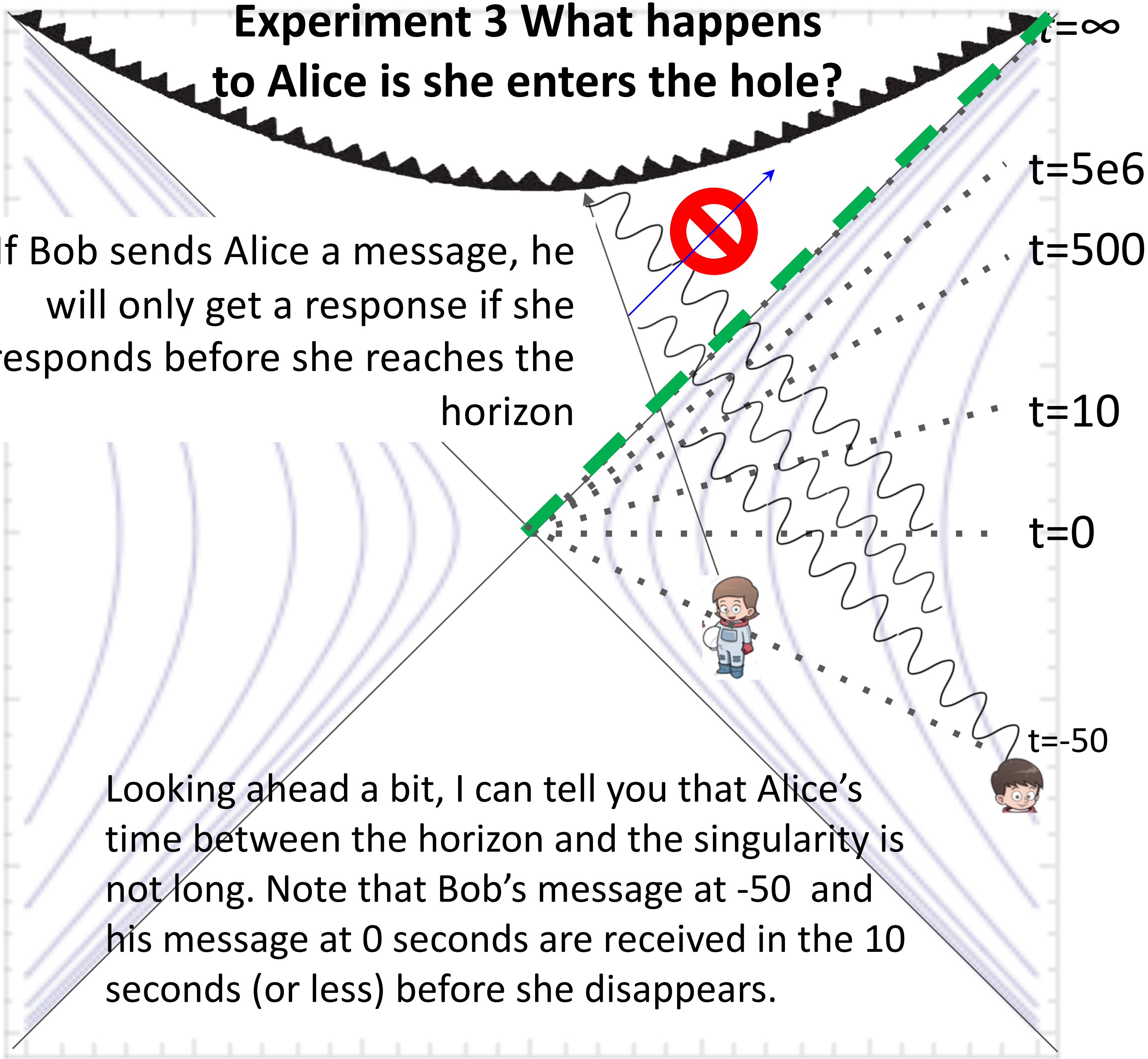
Experiment 3 What happens to Alice is she enters the hole?



If Bob sends Alice a message, he will only get a response if she responds before she reaches the horizon

Looking ahead a bit, I can tell you that Alice's time between the horizon and the singularity is not long. Note that Bob's message at -50 and his message at 0 seconds are received in the 10 seconds (or less) before she disappears.

- Bob keeps sending her messages
- Alice flies through the horizon with no problem
- She keeps seeing Bob's signals
- No effort on her part can save her from destruction
- No effort on her part can result in a signal to the 'outside'
- All her futures involve destruction at the singularity; for a solar mass black hole, she will be gone in a millisecond
- She is likely killed by tidal forces called 'spaghettification' which are tidal forces that we will discuss.

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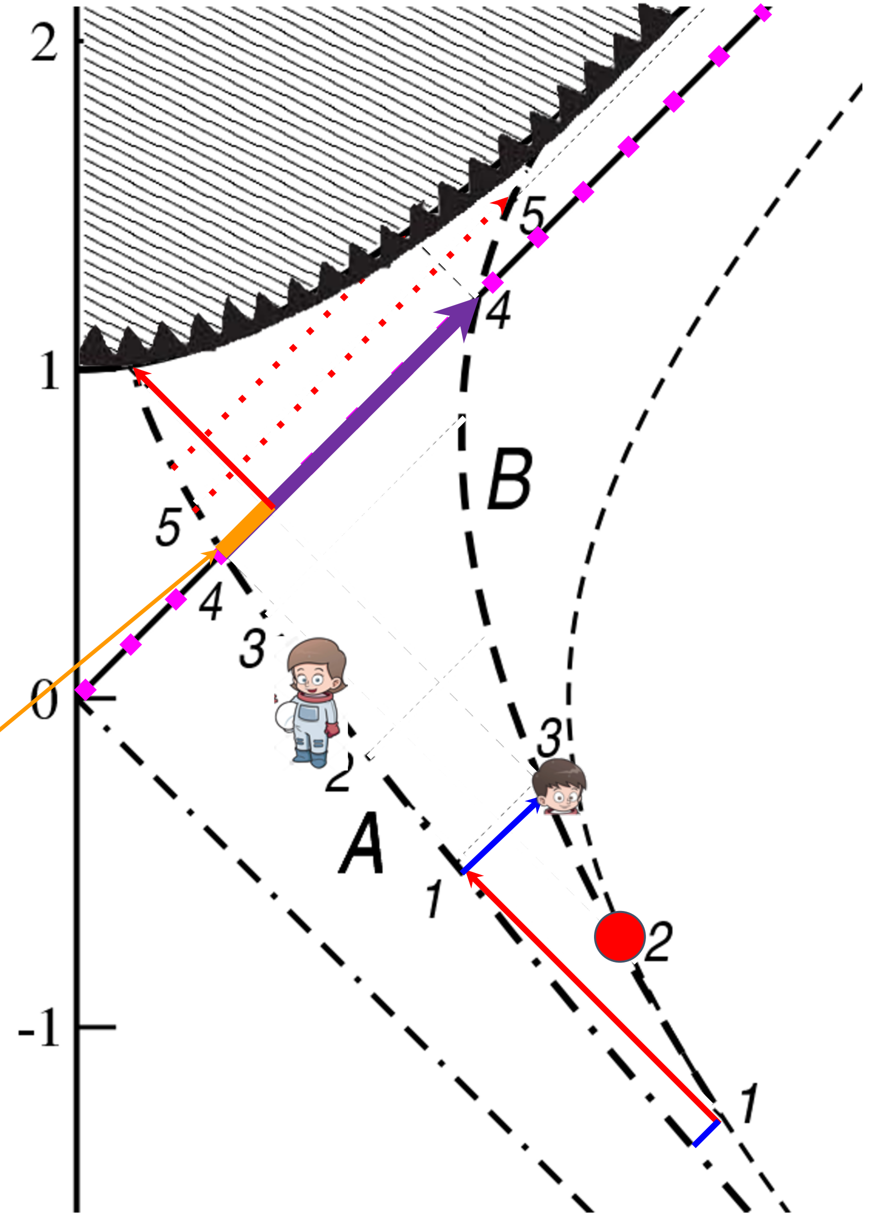
Experiment 4 Both Bob and Alice enter the hole

- Bob and Alice exchange messages while hovering
- Alice descends fi... by shutting offer her engine (free fall). Bob soon follows (**red**...
- Once Alice has p... ...ignal to Bob who may or ... ...e timing involved.
- A distant observ... ...the horizon, while Bo... ...lso slow down and both w... ...horizon.

Note that the curves A and B are the experience of the travelers. They are the only ones who know they have gone through the horizon. All other observers see them freeze/disappear on the horizon

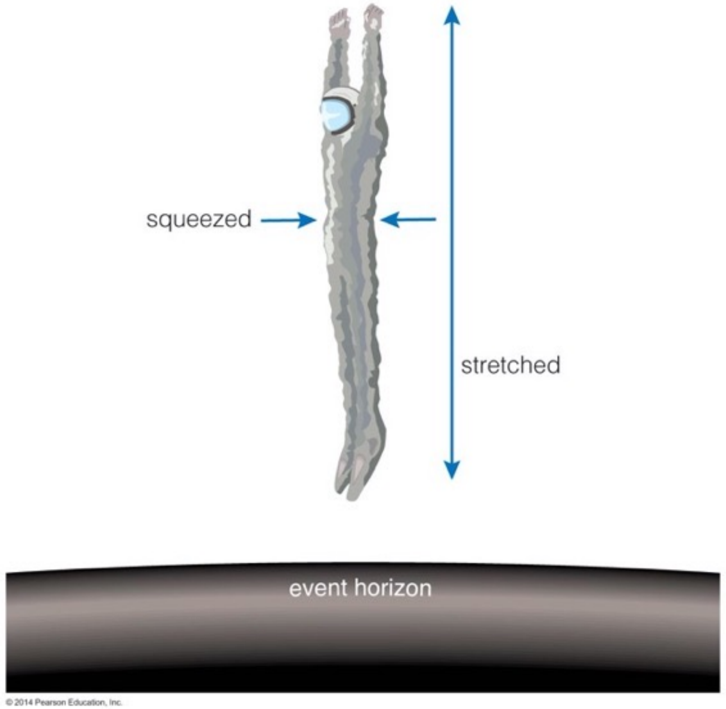
- Should they want to communicate when they are inside the horizon, he must cross it **shortly after her**. Otherwise his message goes to the singularity and/or she does. He can never respond to the dashed messages.

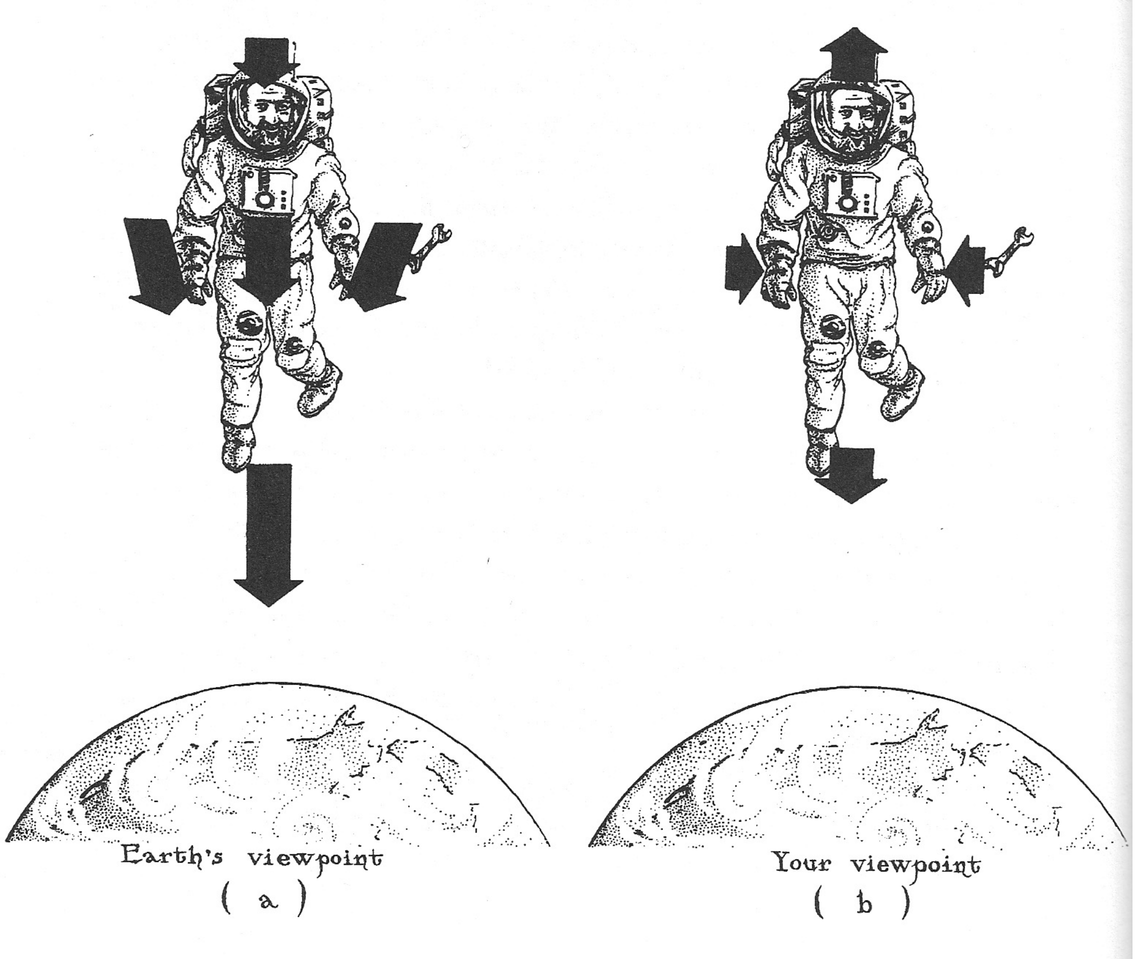


[https://arxiv.org/pdf/1608.07511.pdf←](https://arxiv.org/pdf/1608.07511.pdf) **Highly recommended for those wanting more details.**

Something to be concerned about: Tidal forces

- We can detect nearby masses by watching free-floating particles! Even if we have no other sensors, and cannot see the mass (it might be a black hole)
- Watch unimpeded particles; if they come together, we are in the presence of a large mass





Some details on survival

Object	Mass	$\tau_{collapse}$	Survival time*
Galactic black hole	4e6⊙	60 sec	9 sec
Supermassive hole	2.1e10⊙ [2]	87.5 hours	13 hours [1]

*Based on the strength of human tissue

- The threats are the singularity and tidal forces
- The singularity is seconds to hours away
- Stretching kills you first, your area decreases slowly and eventually, your volume goes to zero
- Again, these calculations ignore the real environment near the black hole

For a solar mass black hole, you'd be killed by the tidal forces before you get to the horizon since the force goes at $1/M^2$

[2] https://www.technologyreview.com/s/614097/astronomers-have-discovered-the-largest-black-hole-ever-observed/

[1] MTW p. 862;

Summary and follow up contacts

- Using Kruskal diagrams, we can explore the following things
    - Causality
    - Communication
    - The appearance of travelers as they approach and enter the horizon
- The Kruskal approach emphasizes the value of exploring novel coordinate systems to observe system behavior **without math**

If you are interested in this topic (or related ones), consider the following additional resources

- I teach a class in Modern Cosmology through a program at Colorado State University.
  - You can see the program schedule and catalog here; Colostate adult education program
- I am a member of a lecture series that occurs over Zoom every month; contact me by email if you'd like notices about that program. It covers a wide variety of technical topics.
- I am writing a book on cosmology for a general audience. It goes beyond what you might find in books by Neil DeGrasse Tyson and other popular authors. If you'd like a free copy of the book, let me know by email.
- I lecture on cruise ships. If you'd like to take a cruise with me (mostly in Europe and the Caribbean), contact me.
- My YouTube channel has many videos of this type on related topics (recent discoveries in cosmology, quantum physics, the physics of renaissance art, methods for finding planets in other solar systems, etc.)
  - Ed's youtube channel
  - My email is edfriedmanis65@gmail.com

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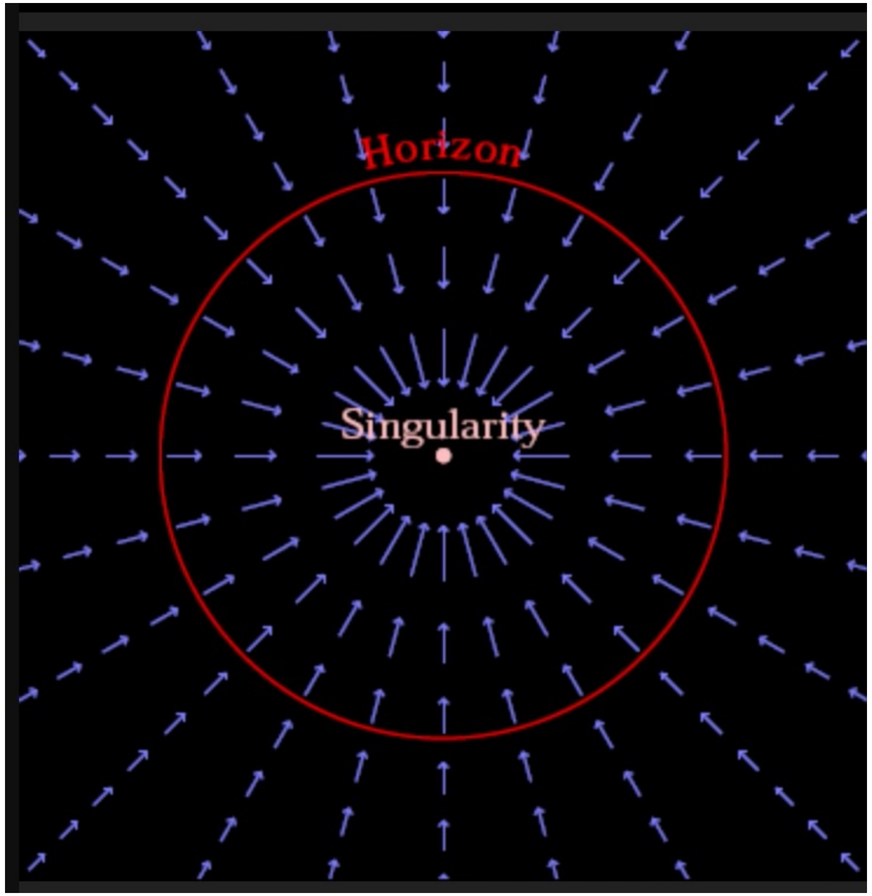
Additional information

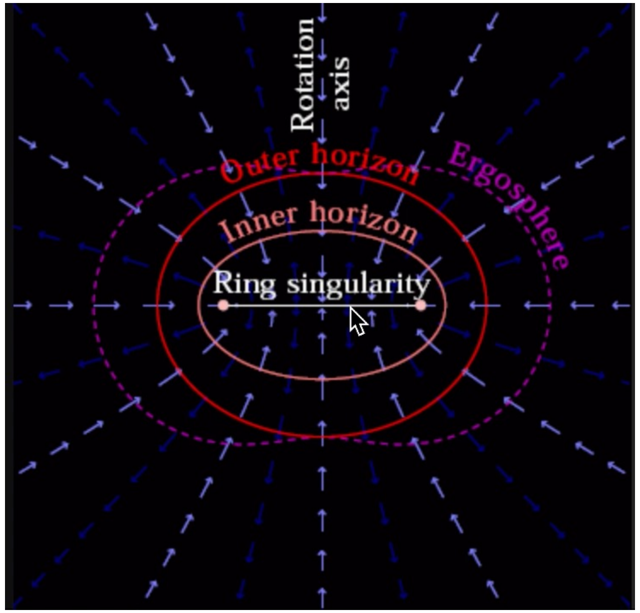
Andrew Hamilton's animations of black holes

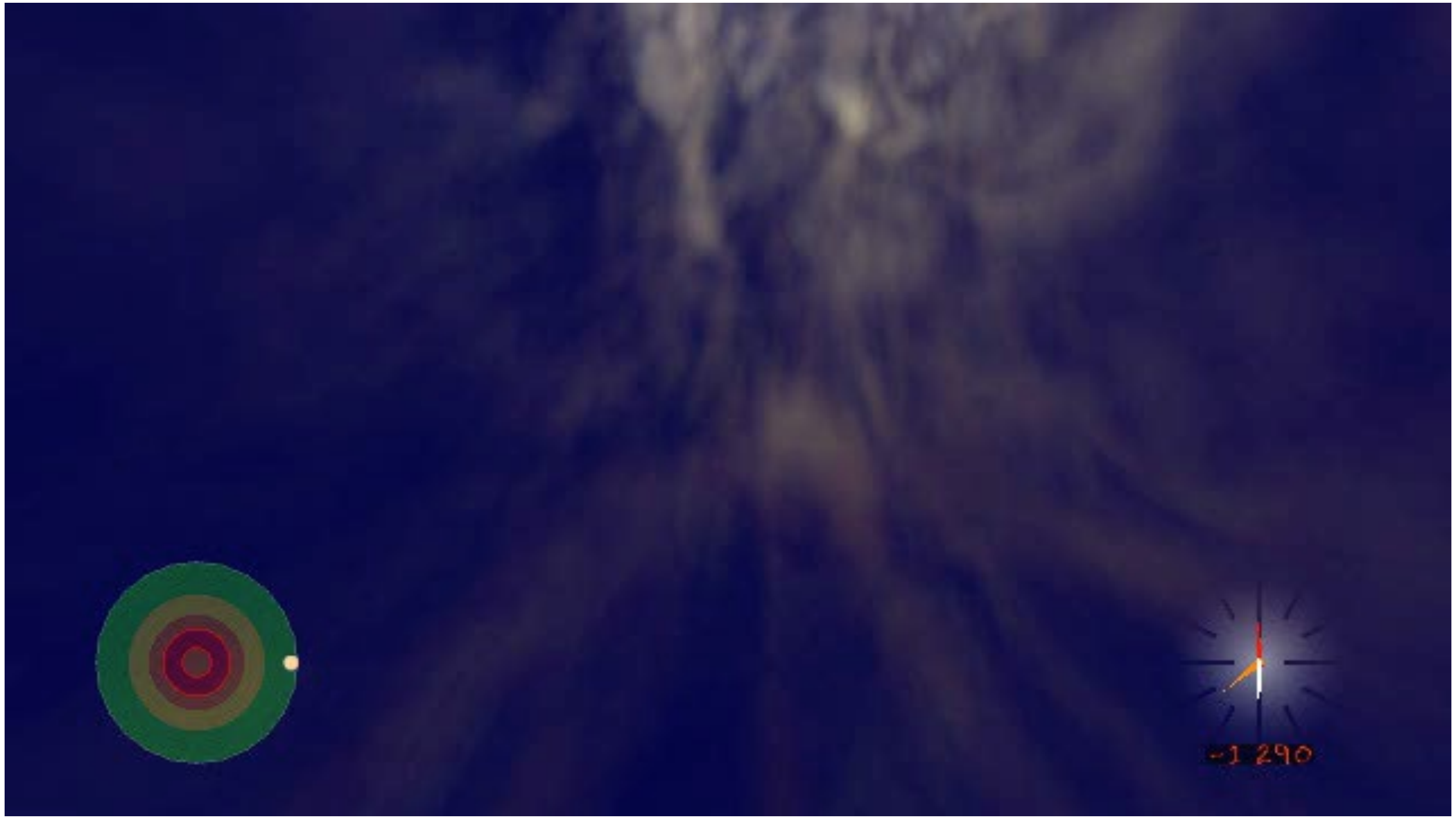


The black hole at left is the simplest type:
No rotation, no electric charge. Inside the horizon, space itself falls into the hole at greater than the speed of light

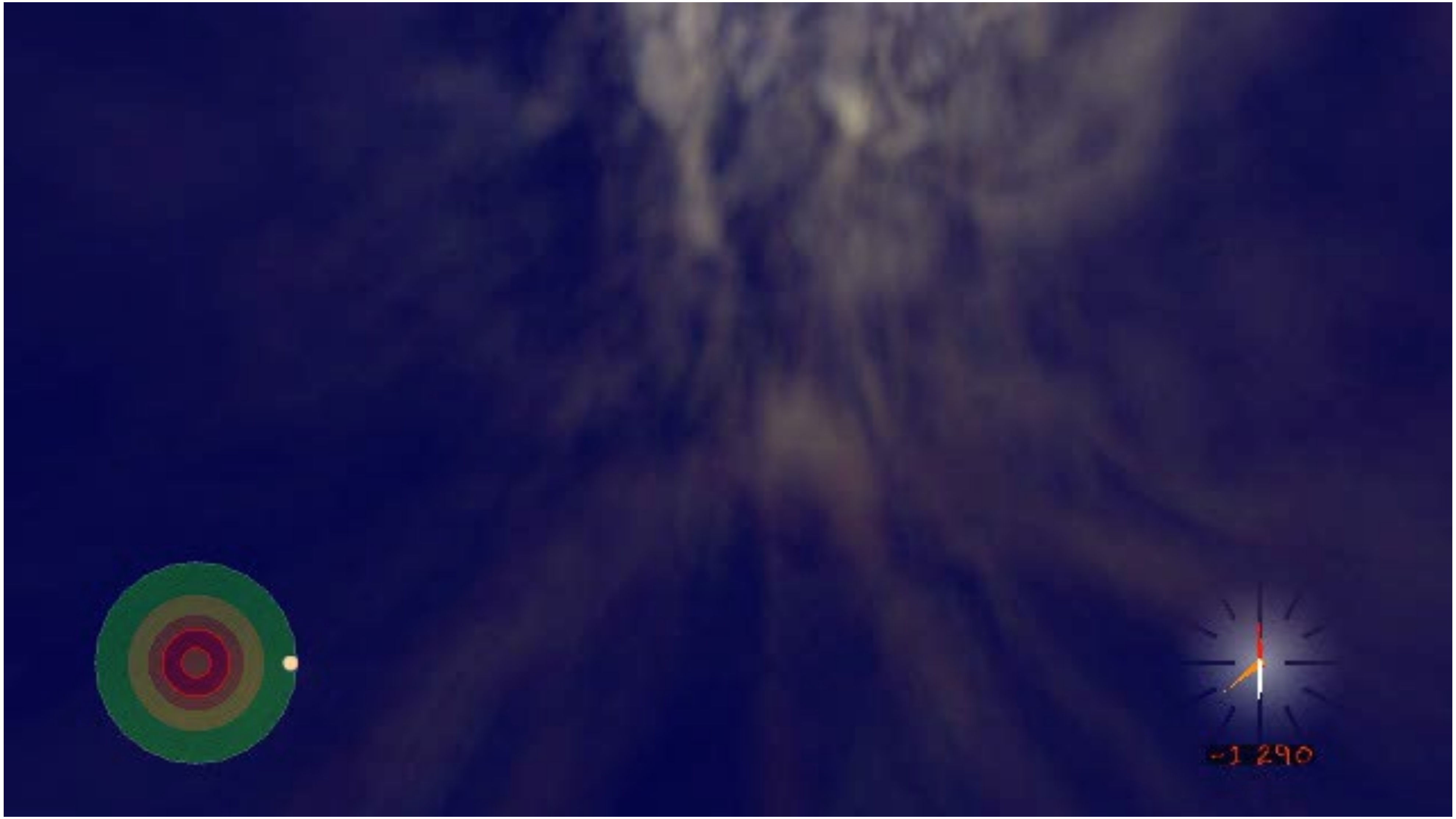
The black hole at right has electric charge. Inside the horizon, space falls into the hole until the electric repulsion becomes overwhelming.

https://jila.colorado.edu/~ajsh/insidebh/waterfall.html


Rotation axis
Outer horizon
Ergosphere
Inner horizon
Ring singularity

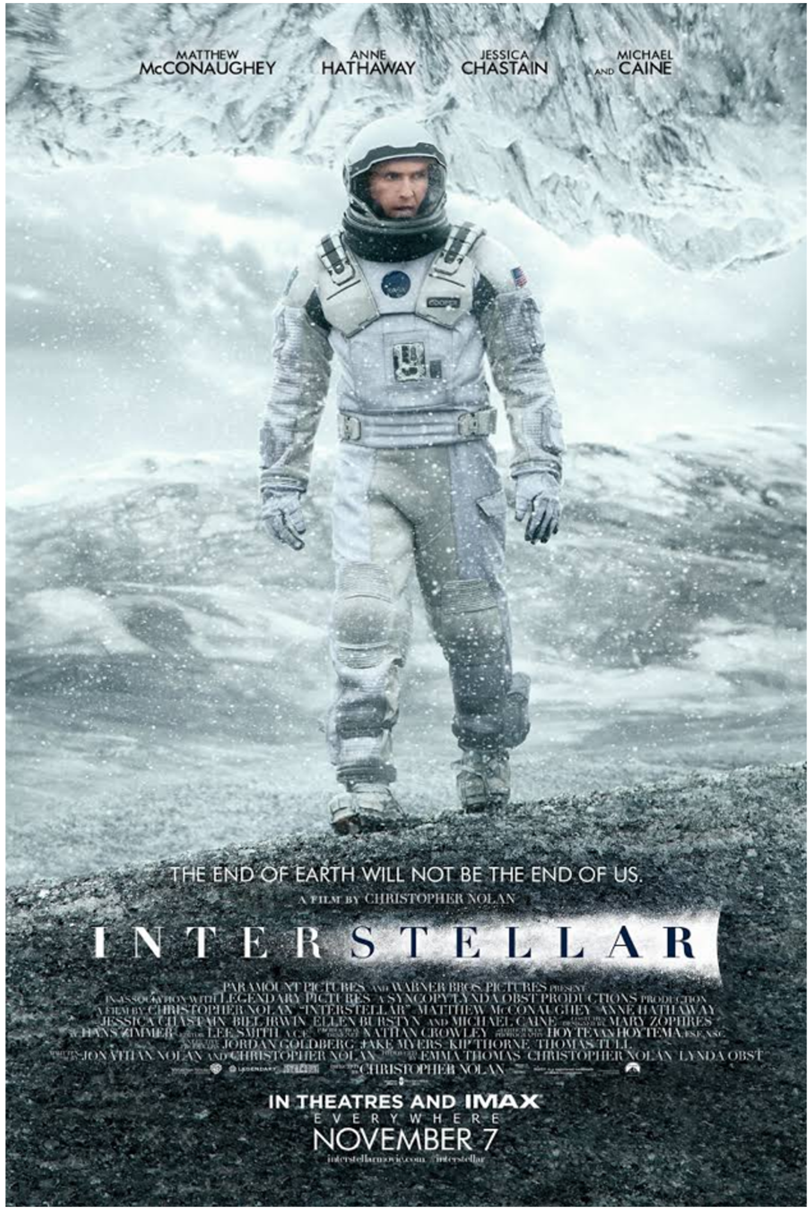

-1 290

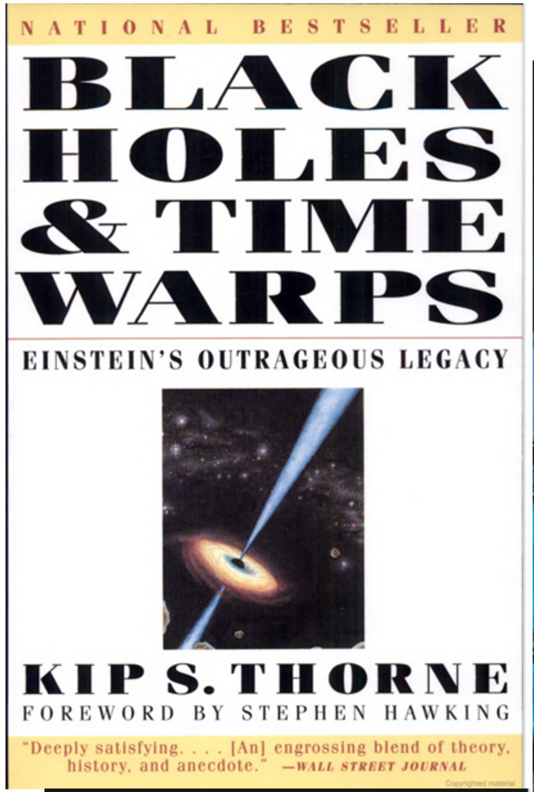
Falling into a black hole

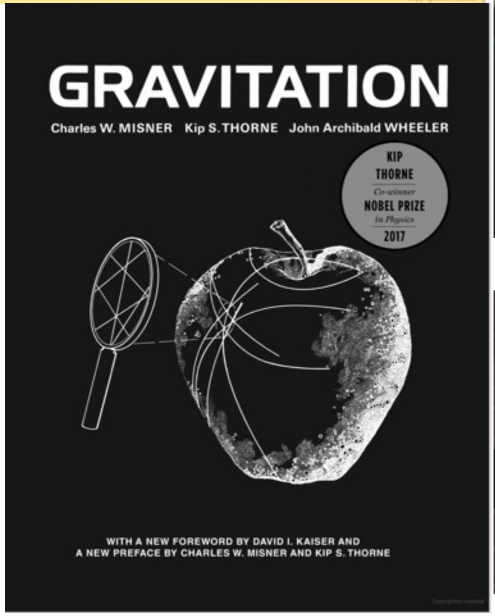


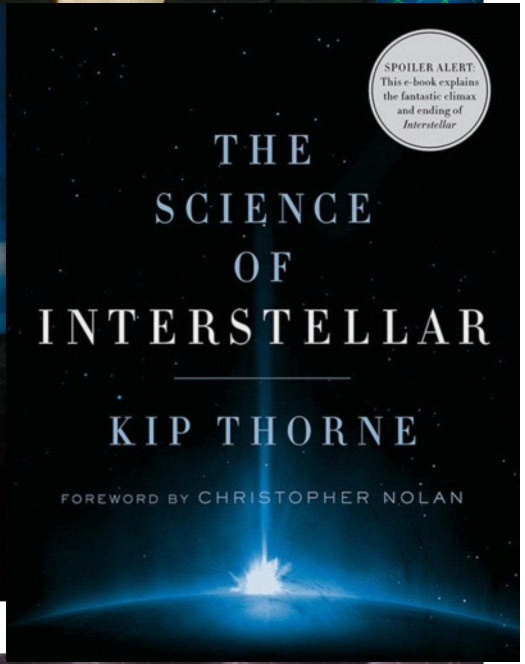
https://jila.colorado.edu/~ajsh/insidebh/realistic.html

Kip Thorne's legacy









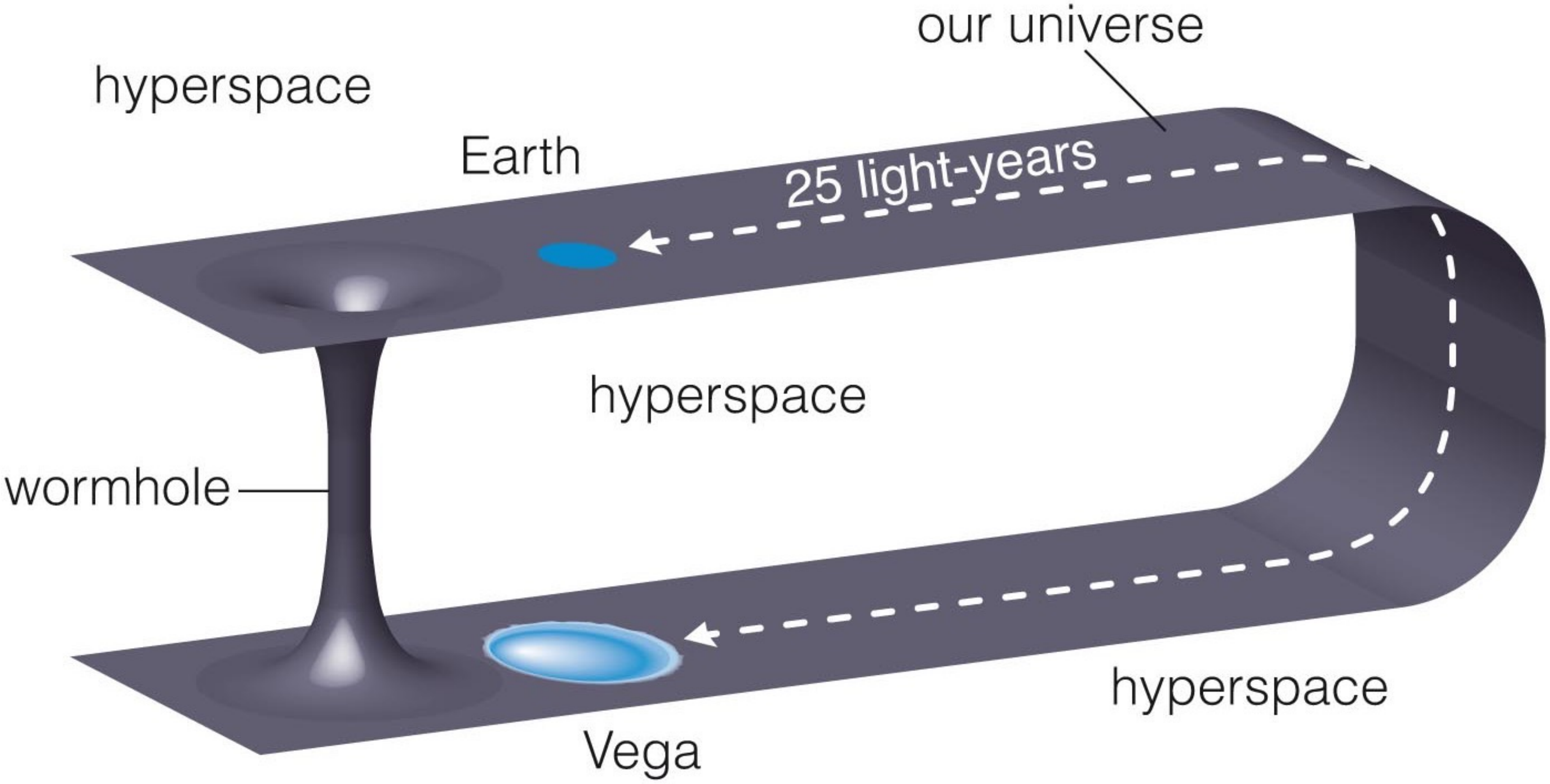
Zoom into M87

https://youtu.be/-22Gv-20LuM

A new view of tunneling through spacetime

With our diagrammatic tools, we can explore the highly speculative issue of tunneling

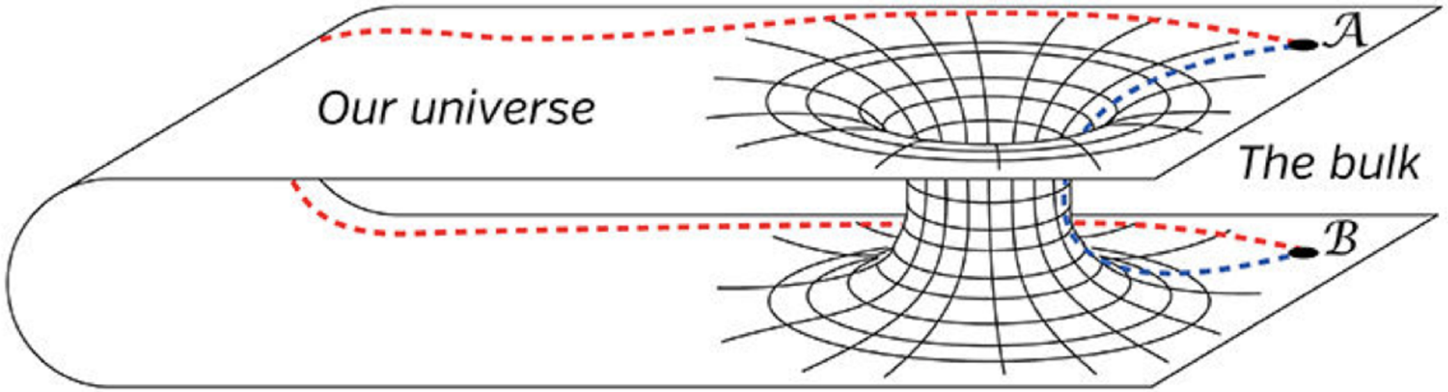
Shortcuts through Spacetime



- Some mathematical solutions of the equations of general relativity allow for shortcuts called *wormholes* that are tunnels through *hyperspace*.

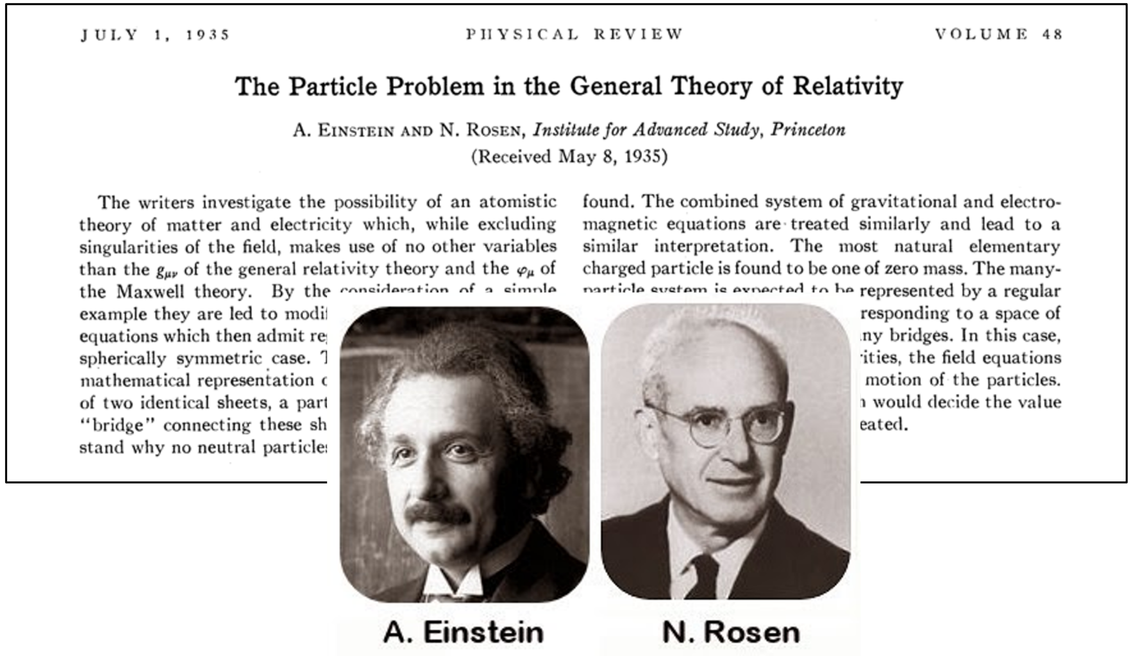
Some history about tunneling

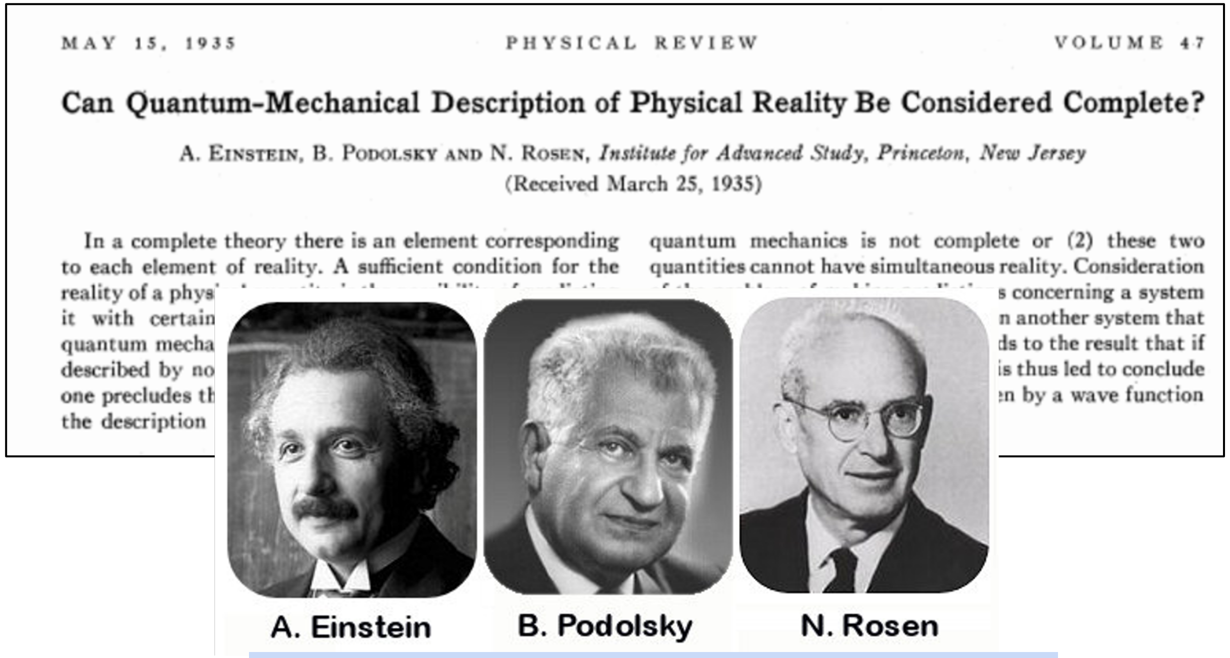
- In 1935 Einstein and Rosen (ER) noted that a ‘bridge’ could be created from one place in the universe to another
- In 1988 Thorne and his students published a speculation about wormholes that created controversy[1].
- An enabling technology for such holes would be ‘exotic matter’



Throughout this lecture, when you see a circle on a 2d drawing, it implies a sphere in 3 dimensions

A new approach sets aside exotic matter by using concepts posed within 2 months of each other





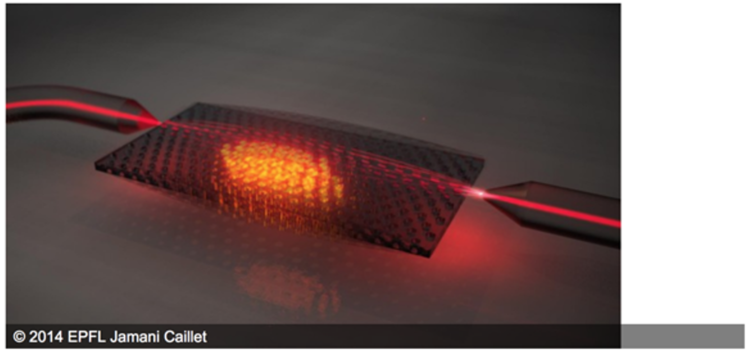
Bridges in spacetime

Spooky action at a distance

ER=EPR

Entanglement is key to the new view of tunneling

Recent headlines of successful entanglement



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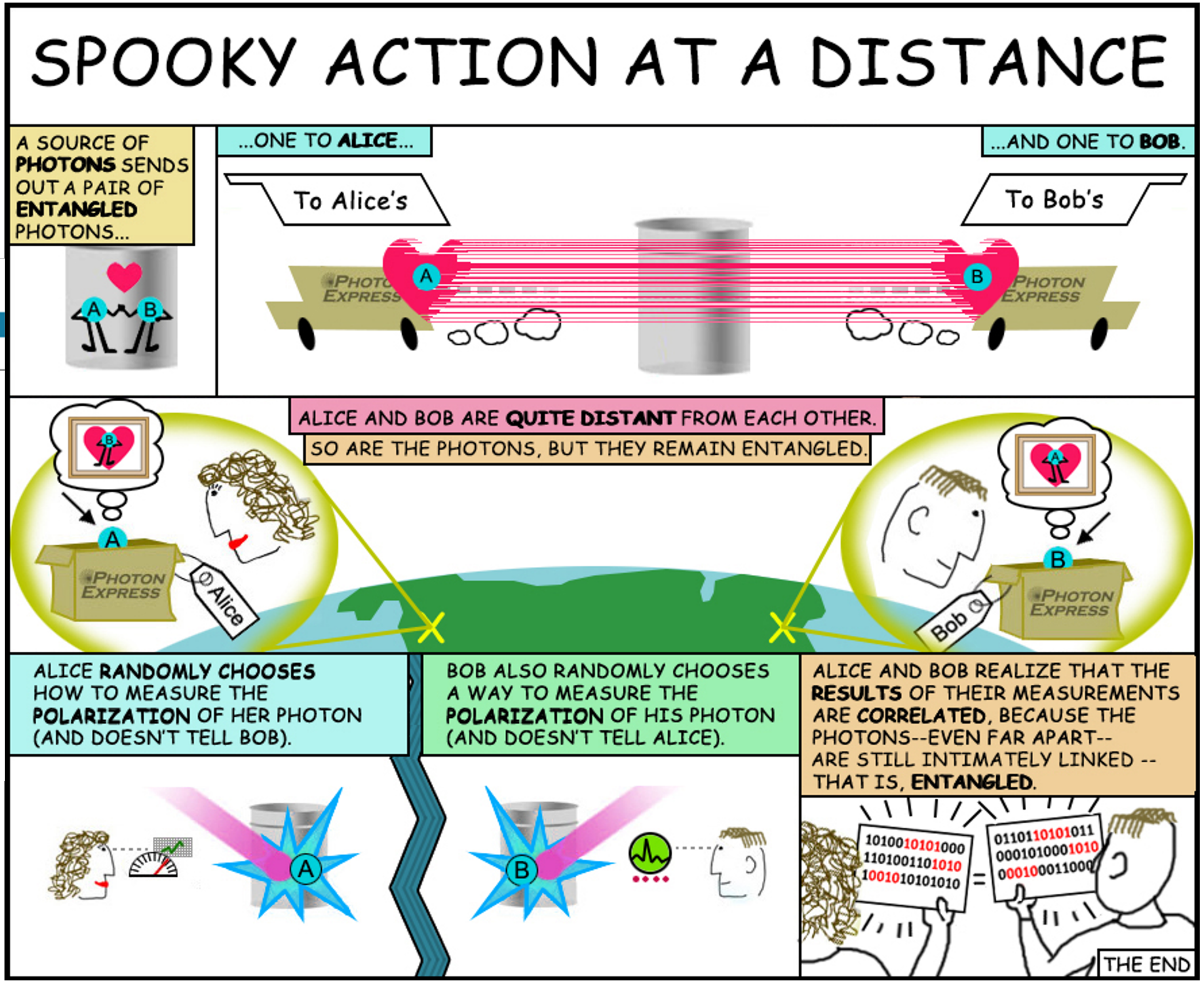
Quantum entanglement made tangible

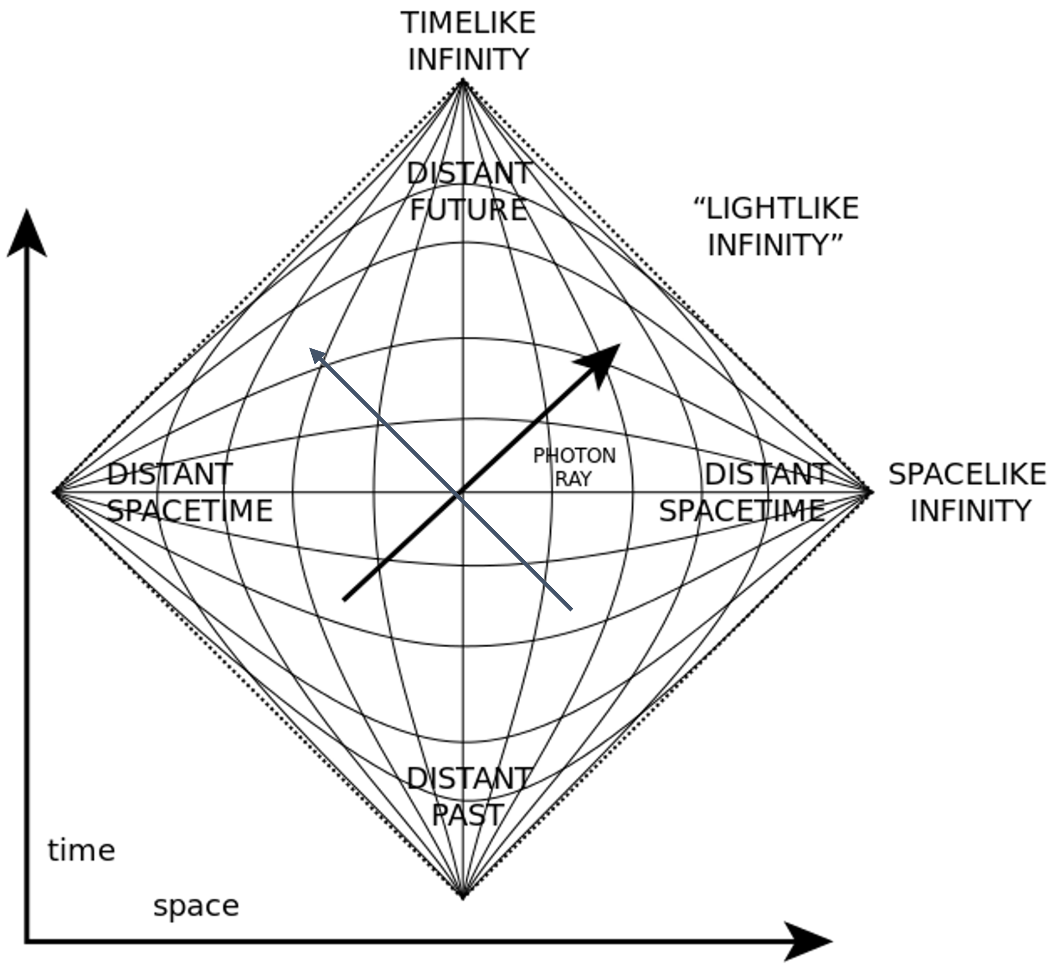
© 2014 EPFL Jamani Caillet

06.10.14 - EPFL scientists have designed a first-ever experiment for demonstrating quantum entanglement in the macroscopic realm. Unlike other such proposals, the experiment is relatively easy to set up and run with existing semiconductor devices.

In the June 16, 2017, issue of *Science*, Yin et al. report setting a new quantum entanglement distance record of 1203 km, demonstrating the survival of a 2-photon pair and a violation of a Bell inequality, reaching a CHSH valuation of 2.37 ± 0.09, under strict Einstein locality conditions, from the Micius satellite to bases in Lijian, Yunnan and Delingha, Quinhai, increasing the efficiency of transmission over prior fiberoptic experiments by an order of magnitude.[82]



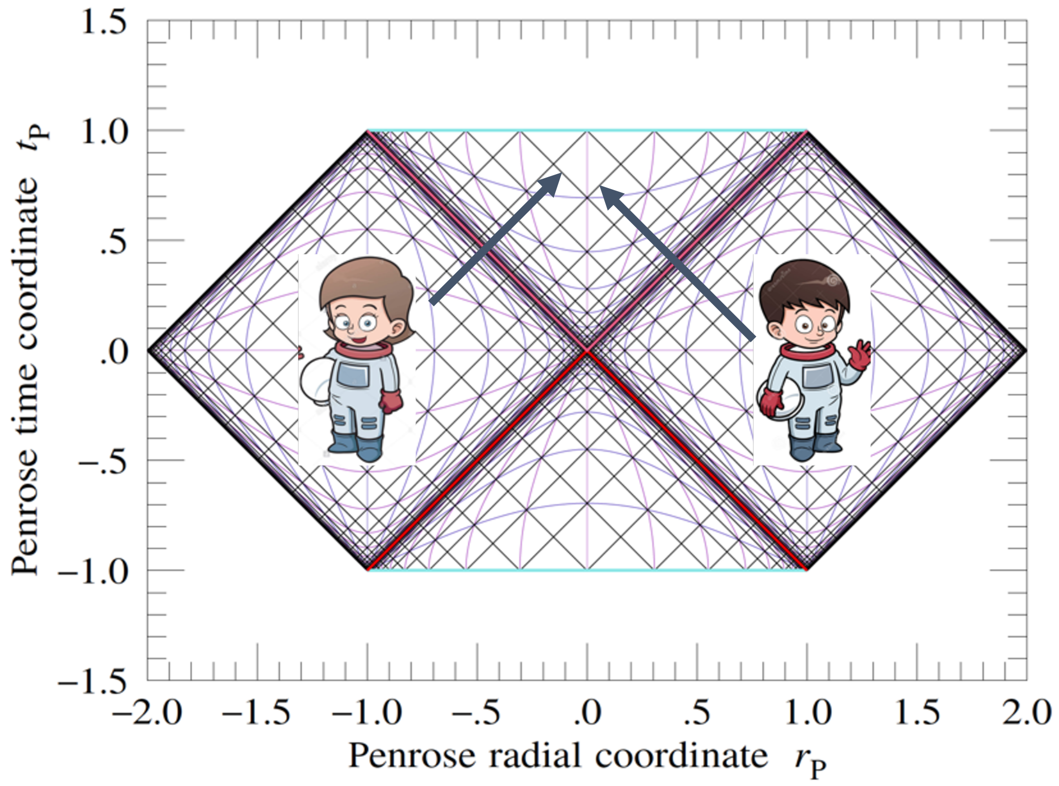
The Penrose diagram provides a way to overcome the spatial limitations of Kruskal coordinates and preserves photon motion at 45°

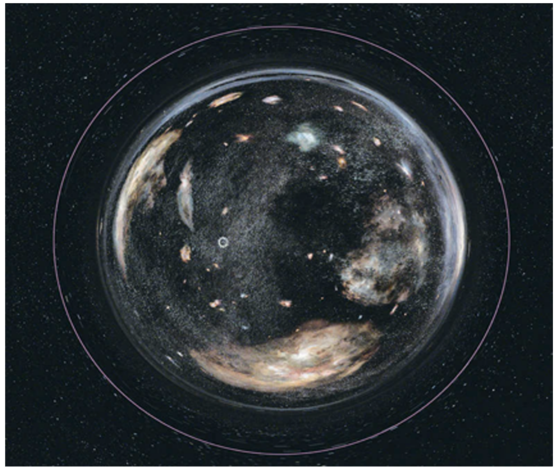


- Compression of the dimensions at 45° allows us to 'compactify' all of space and time into a small drawing. This set of images shows flat spacetime (no black hole)
- The Penrose diagram at left has no mass to distort spacetime or create a horizon.
- Any signal produced anywhere in this space can reach 'Lightlike Infinity'. **This is not the case if a horizon exists.**

A new way to 'time travel'

- Form a pile of entangled quantum pairs (particles or photons)
- Separate the members of each pair until you have enough to form two black holes
- Due to entanglement, the two holes are actually two manifestations **of the same hole**
- If you jump into your black hole, you appear in the interior of the other and vice versa (since they are the same hole).
- By entering the hole, you disturb the material already there which is intimately connected to the material in the other hole. Both are affected.





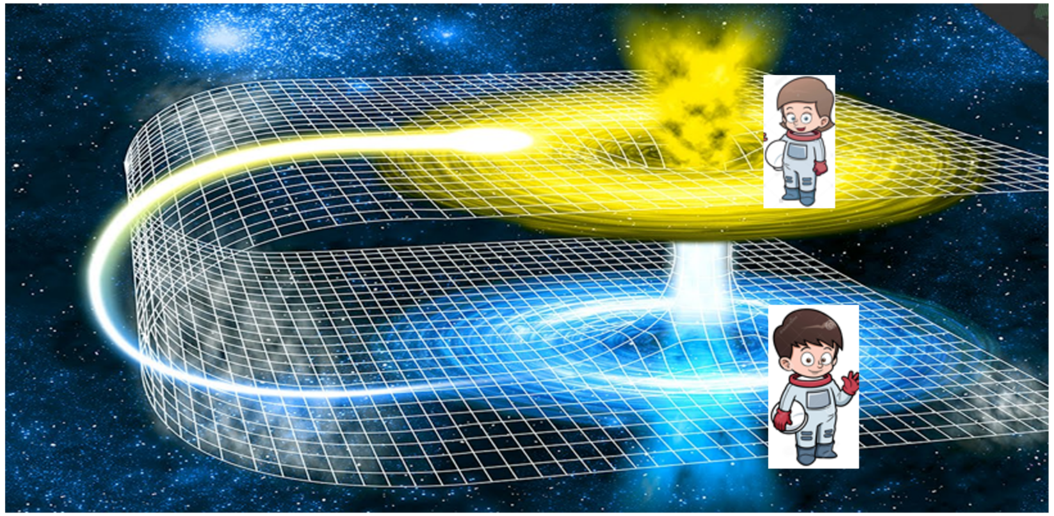
Each would see something like this.

Kip Thorne, *The Science of Interstellar,* 2014

https://www.youtube.com/watch?v=OBPpRqxY8Uw&t=2085s

Alice and Bob each have a horizon in front of them. They can share information ONLY if they are willing to sacrifice themselves in the process.

- They cannot report on their success since they have committed to die in the shared hole
- They 'meet in the middle' **for as long as they avoid the singularity or lethal tidal forces**
- This resolves the unsatisfactory implications of being able to 'kill your grandfather' since the travelers move in space, not time.



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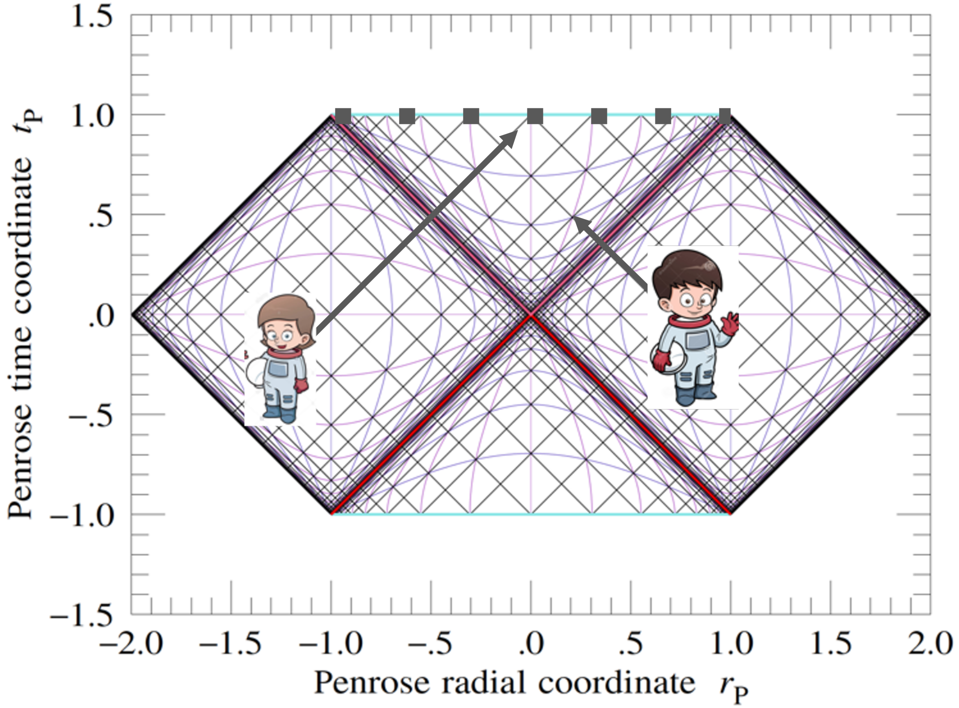
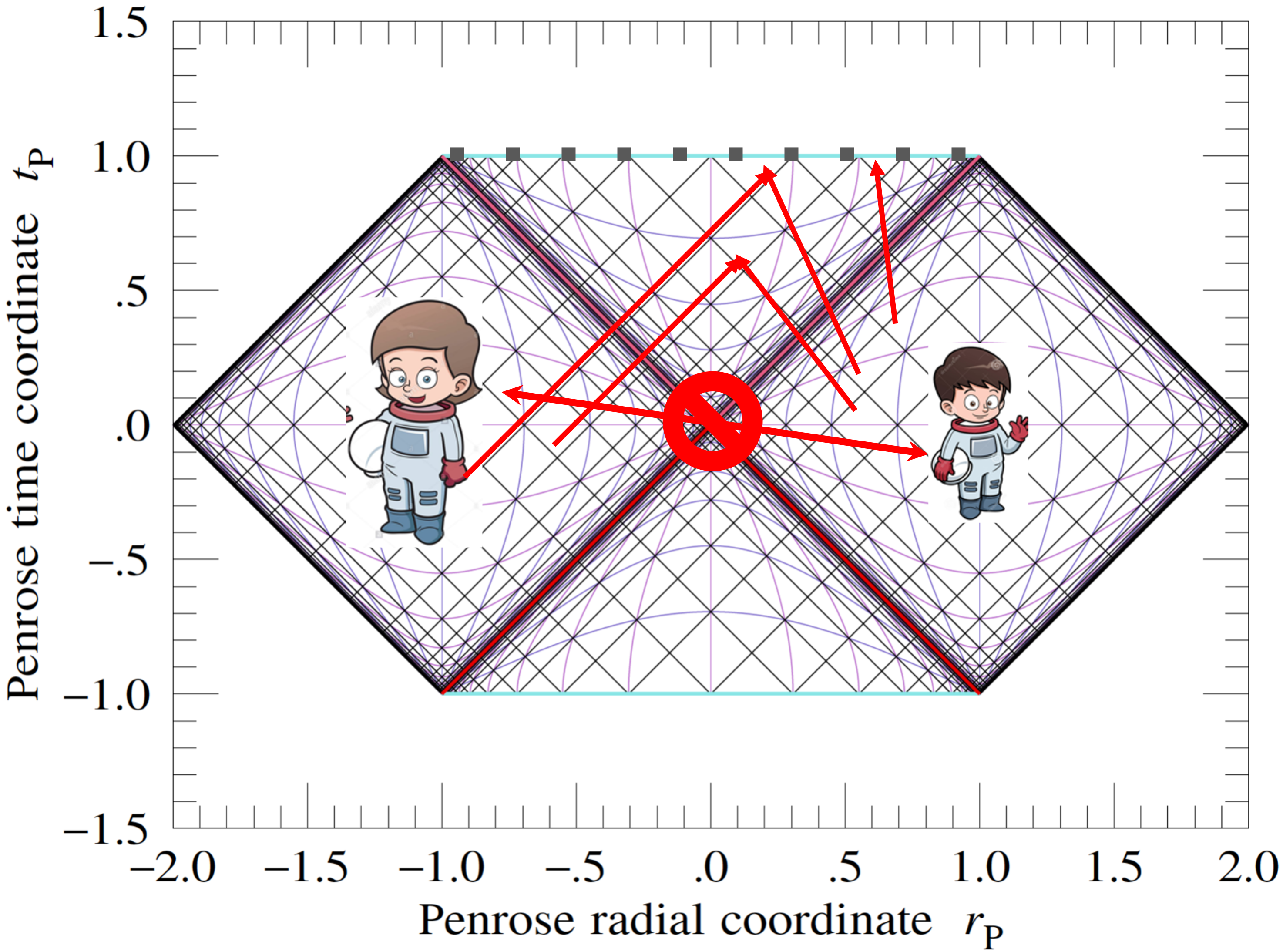


If Alice and Bob are in two places, each connected with one hole, can she send him a signal before he perishes?

- They cannot communicate until one of them enters the common hole
- With careful timing, Alice can send a signal to Bob
  - If she waits too long, he is dead
  - If he waits too long, she is dead
- If the hole is large enough, she can meet him in the hole
- Her position when she sends the signal determines how at risk she is



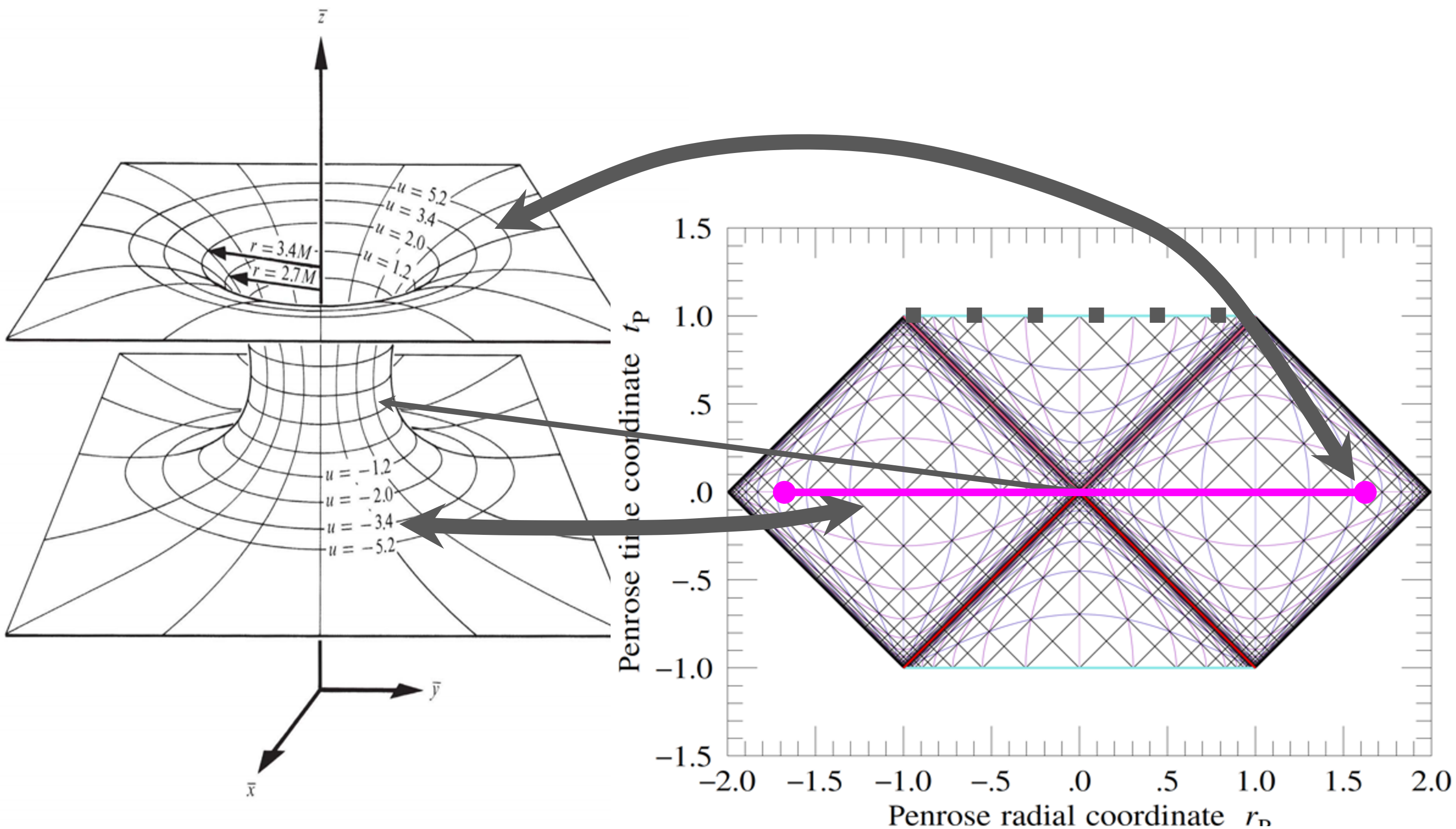
Mouth in Dublin

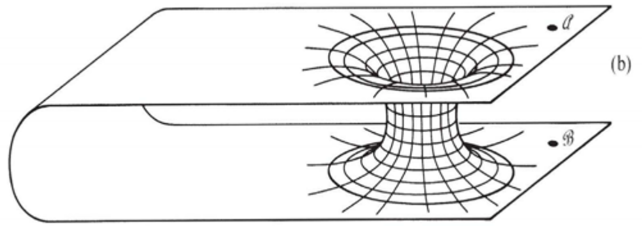
Mouth in California Desert

Conclusions about wormholes

- The science fiction concept of going back in time is refuted
- Travel to another place is allowed and does not violate the limits of the speed of light since creating and separating the 2 black holes involves a process in which mass moves (which is limited by the speed of light)
- The success of any experiment is hidden from our universe by the horizons of the black holes; experimenters are destroyed in the process.
- This is an active area of research and its conceptual and mathematical advances are being used to study condensed matter physics, superconductivity and other fields.
- A key residual result is that there is growing evidence that entangled particles are the vehicle by which spacetime is created.
- Surprisingly, this new approach has revealed new physics <u>but without a theory of quantum gravity which was always presumed to be essential before progress could be made.</u>

Highly speculative access to another universe



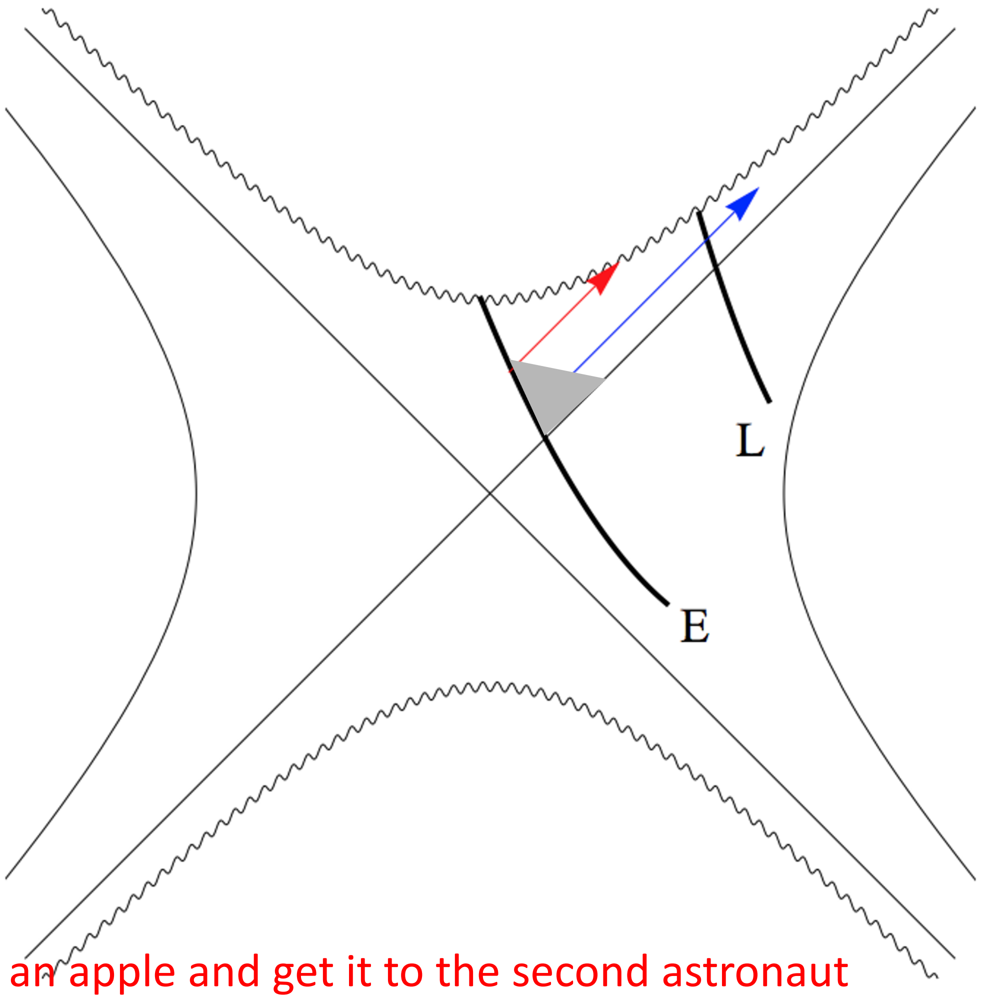


But remember that velocities exceeding ***c*** are not allowed so this type of travel is excluded

- No violation of the speed of light
- Any success they have is hidden from observers outside the hole
- The amount of mass needed to create each hole is not restricted. A black hole can be made with a small mass (if compressed to small enough size) BUT it will evaporate quickly.
- A 1-second-life black hole has a mass of $2.28{\times}10^5$ kg, about the size of a herd of elephants.

Another experiment they can do involves not meeting, but sending signals to one another

- An early traveler (E) can send a signal to a later arrival (L) but with restrictions; wait too long and L has hit the singularity before getting the signal
- It is even harder to send an object (which has a velocity less than *c*) from E to L as shown by the triangle
- The solution seems to be to have E send a signal immediately upon entering the hole and hope that L sees it.
- E will not find out if the experiment was a success



https://arxiv.org/pdf/1211.6767.pdf

You can throw an apple and get it to the second astronaut

Additional sources

https://amostech.com/TechnicalPapers/2009/Poster/Zhou.pdf

https://eventhorizontelescope.org/blog/eht-status-update-may-1-2018

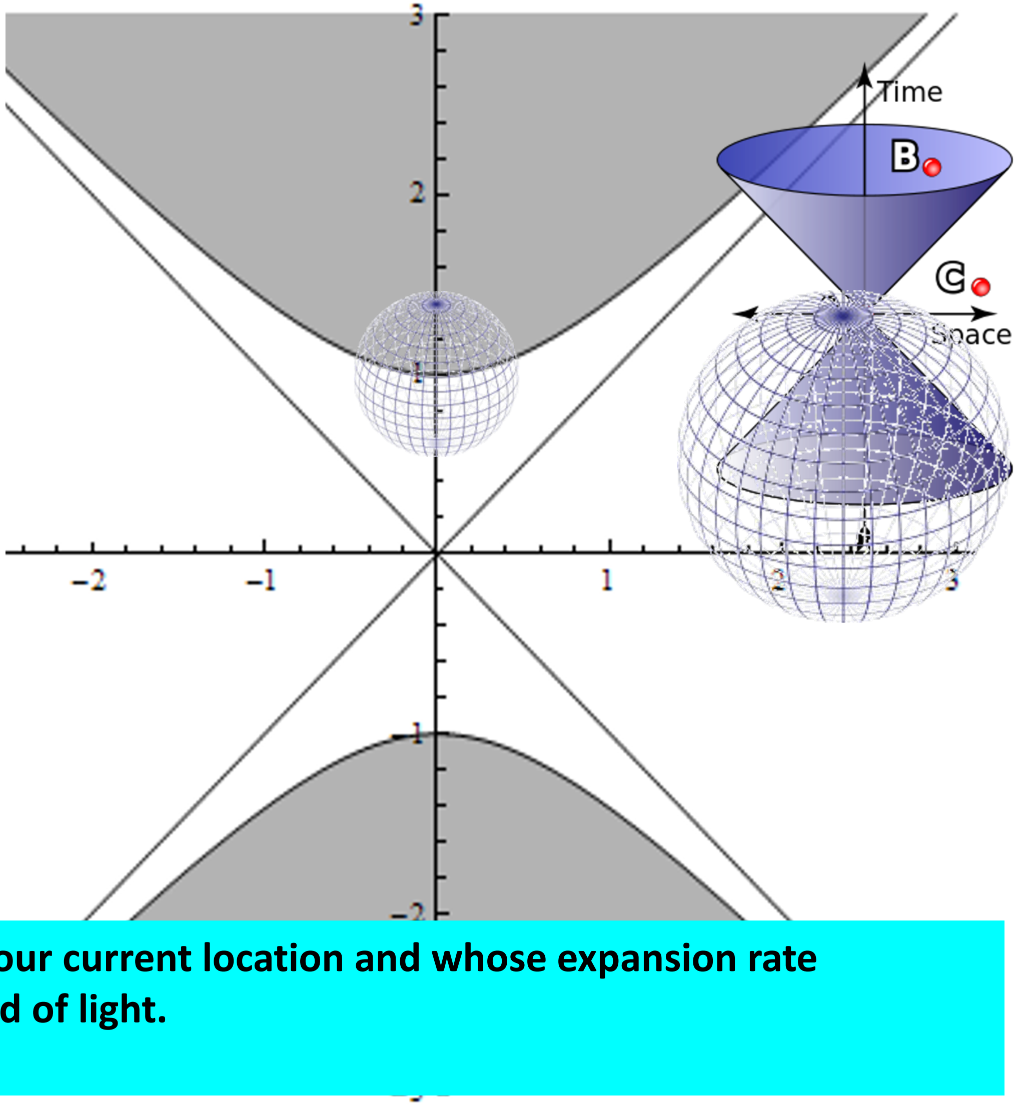
https://arxiv.org/pdf/1806.09740.pdf

More advanced topics

- Starting from the Kruskal diagrams of the last lecture, we explore how universes might be coupled through a unique type of black hole
- We'll also fill some holes overlooked in the prior lecture
- A few equations will help us conceptualize

Spacelike motion become timelike when crossing the horizon

- As the radius becomes smaller, it progresses inward to the horizon, then changes to a time coordinate
- Your future is not a place; it is a time and that time is a measure of how long you will survive until you are carried to the singularity.
- Note that the drawing suppresses 2 spatial dimensions. One dimension is restored by the light cone. **The past light cone shows the space and time regime that defines your present condition. The future light cone defines the spacetime regions you can explore.**



- **In areas I, III and IV each point represents a sphere centered on your current location and whose expansion rate (defining the motion of a traveler or light ray) is limited by the speed of light.**
- **In area II, the sphere of your future is centered on the singularity.**

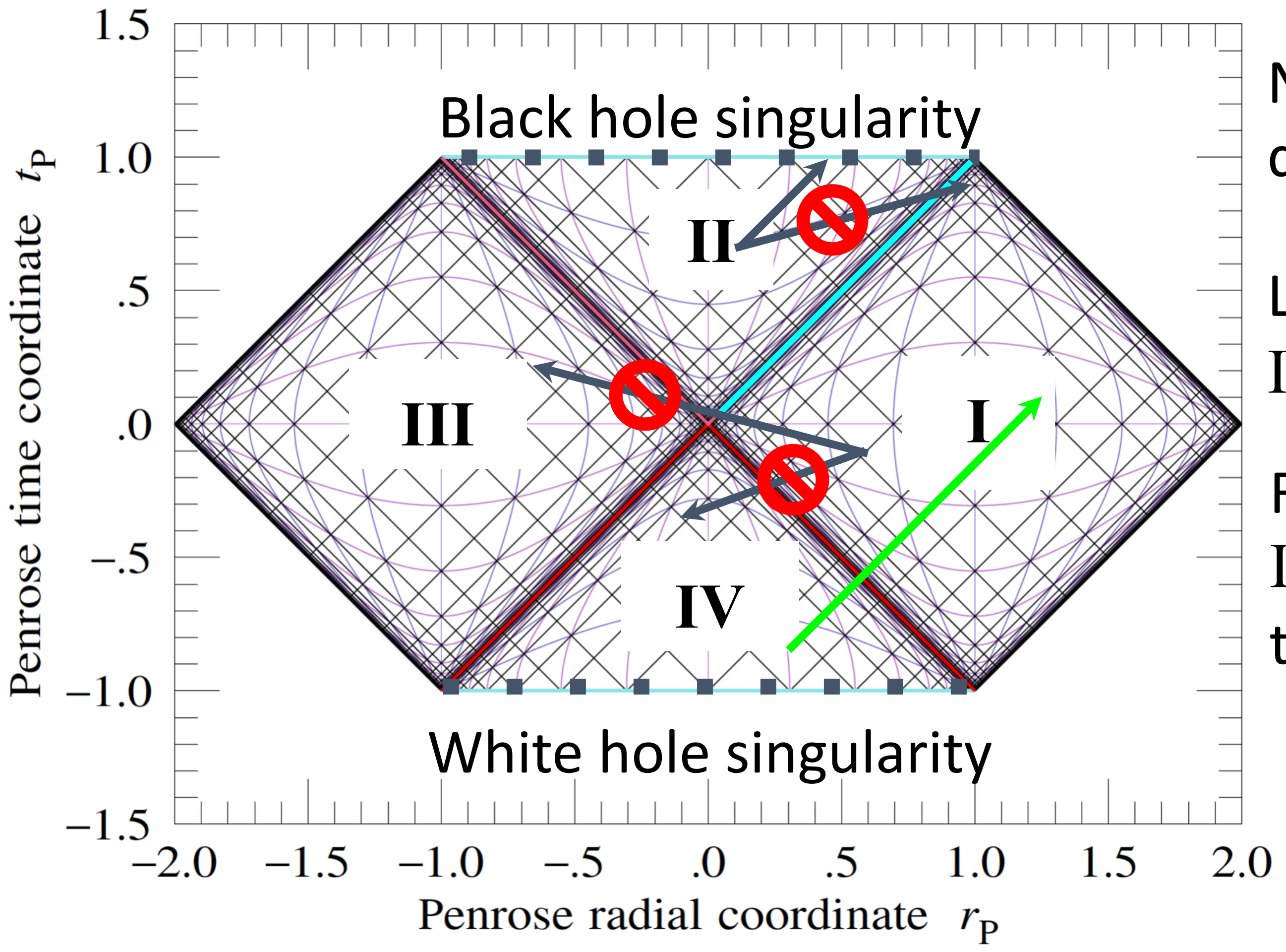
Penrose diagrams

Using this coordinate system, we can explore all of space and time in one drawing AND we can speculate about worm holes

Implications of the Penrose diagram

Not allowed by the speed limit

No escape of light or matter from Region II



No signal from Region II can be detected in Region I

Light created in the early universe (Region IV) is sensible in Region I today (CMB)

Region I cannot send a signal to Region III or IV. Note also that these moves obviate time travel.

One can speculate that Region III is part of another universe or another place in this universe.