Class 26 : Wormholes and Time Machines

ASTR350 Black Holes (Spring 2022)

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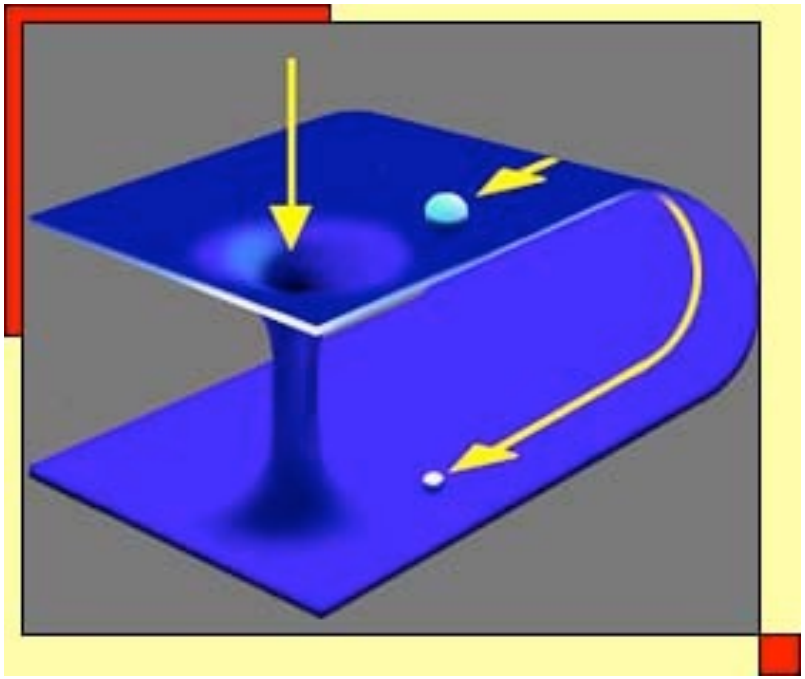
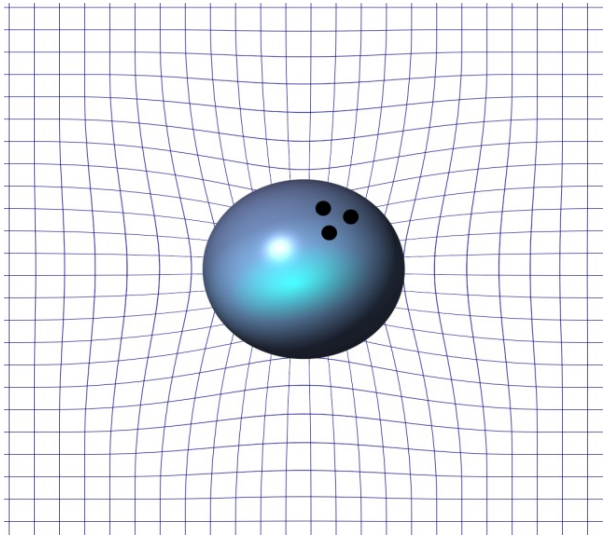
Last time, and this time

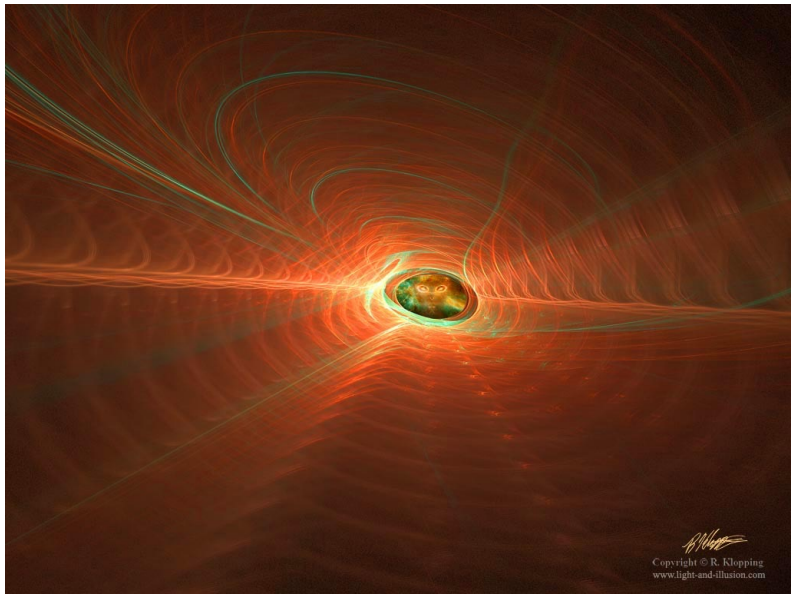
- Last time we talked about quantum mechanics and Hawking radiation. There are some strange implications that we'll explore in the next class
- But now we'll really get weird and talk about wormholes!
- I use online slides from two main sources. One source I can't identify: it seems to have been from Astronomy 102 at Penn State, taught by a "Watson" in 2001, but I'm not sure who that is (and Watson's main source is "Black Holes and Time Warps", by Kip Thorne)
- The other is a presentation by two students, Melissa Meikle and Melody Golobic, at Santa Rosa Junior College
- Credit where credit's due!

What are Wormholes?

- Hypothetical tunnel connecting two different regions in space-time
- Traveling through a wormhole takes less time than traveling between the same starting and ending regions in normal space
- In theory, the ends of wormhole could be intra-universe or inter-universe

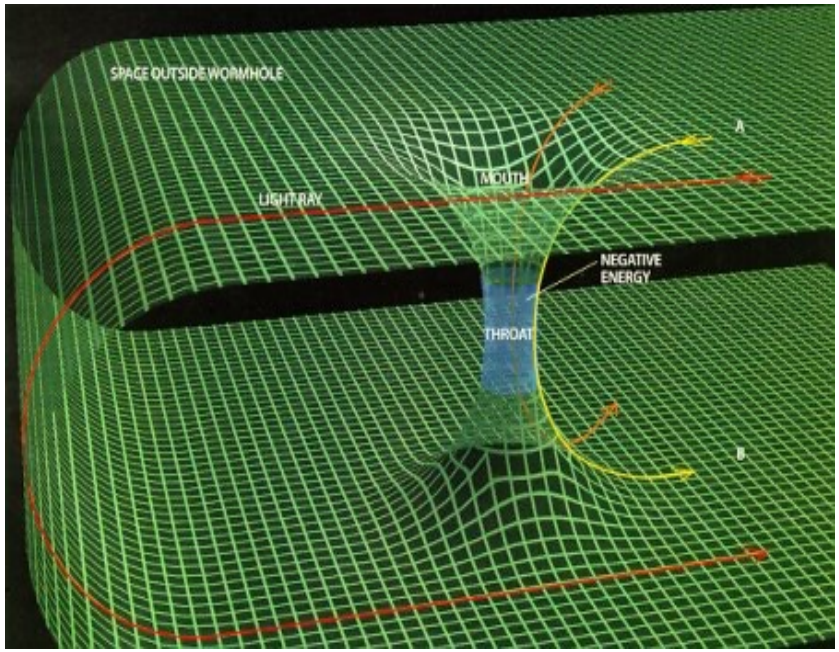






- Weight added to a piece of fabric will cause sag towards the center
  - Supermassive black holes cause a tear in space-time and this tear is the wormhole
  - These two regions would meet and form a wormhole connection

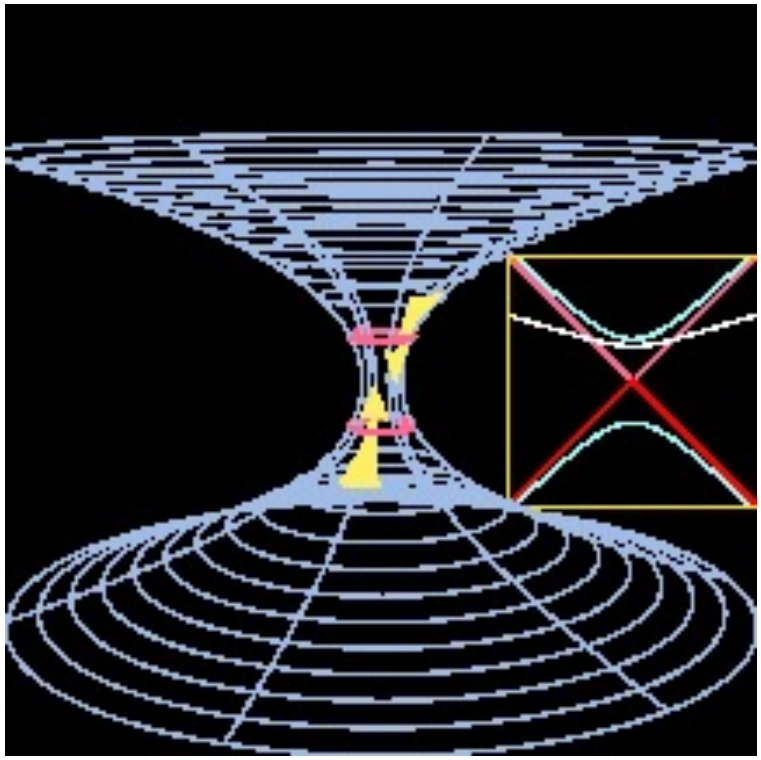
Shape



- Defined as shortcut through space and time
- Has to fold the 2D concept of space and time to create a 3D situation
- Becomes the bridge from one dimension to the other
- Made up of: 2 mouths and a throat

Properties

- As initially envisioned (by Einstein and Rosen), highly unstable
- Most likely would collapse instantly even if the smallest amount of matter (i.e., a single photon) went through
- So the question is: can there be a *traversable* wormhole?



Looking for traversable wormholes

- Carl Sagan's Novel *Contact* in 1985 prompted physicist Kip Thorne to develop a space transport system which led him to a new solution to the equations of general relativity describing large traversable wormholes.
  I was at Caltech at the time, so I saw this develop!

Jodie Foster as Ellie Arroway in the movie "Contact"

Construction/destruction of a wormhole

Expanding singularities

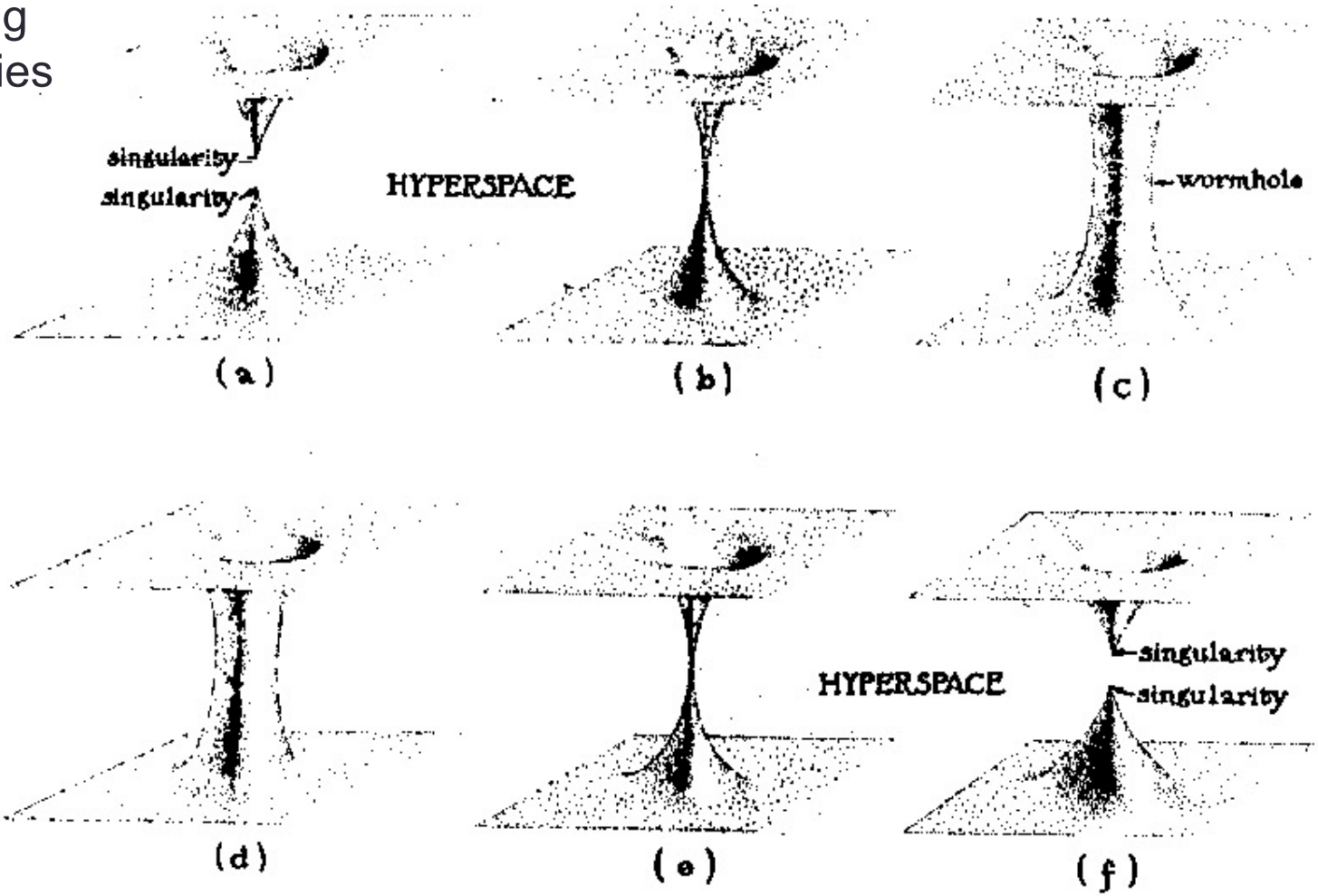
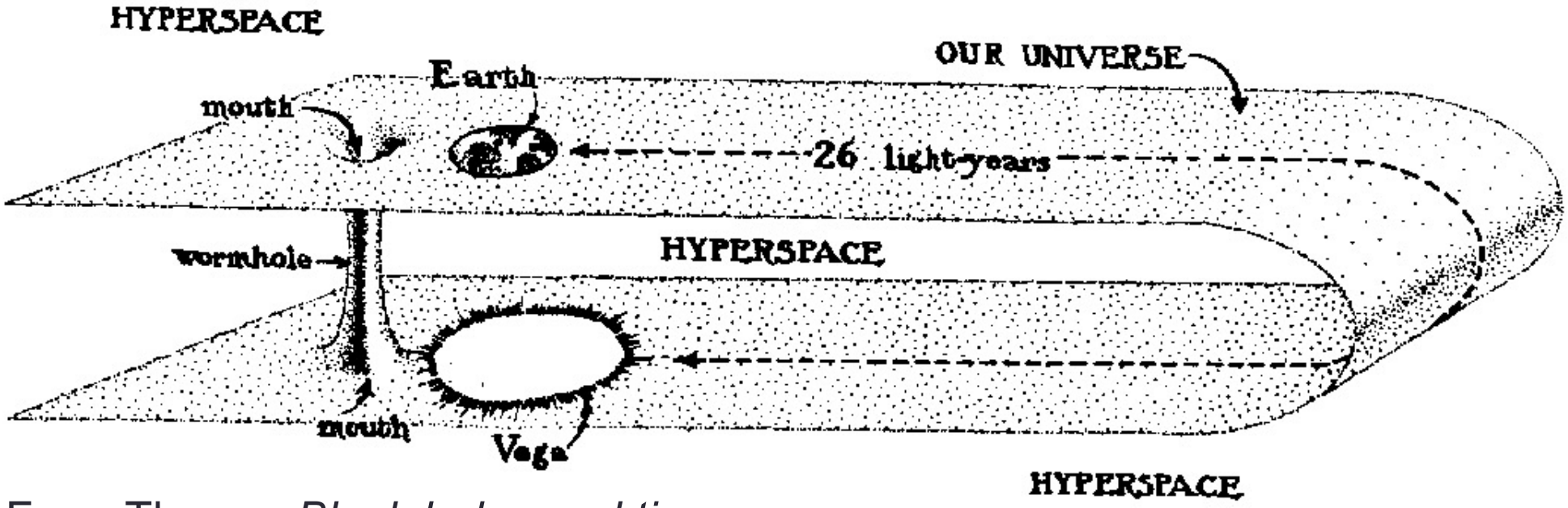


Figure from Thorne, *Black holes and time warps.*

Contracting singularities

A hyperspace shortcut *via* a wormhole

- An **embedding diagram** of a wormhole with the properties described in Carl Sagan's novel *Contact*, that was used by the lead character, Ellie Arroway, to travel to the neighborhood of Vega and back in about eighteen hours.

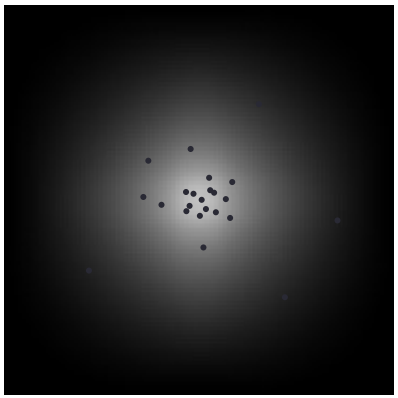


From Thorne, *Black holes and time warps*

Methods of wormhole construction

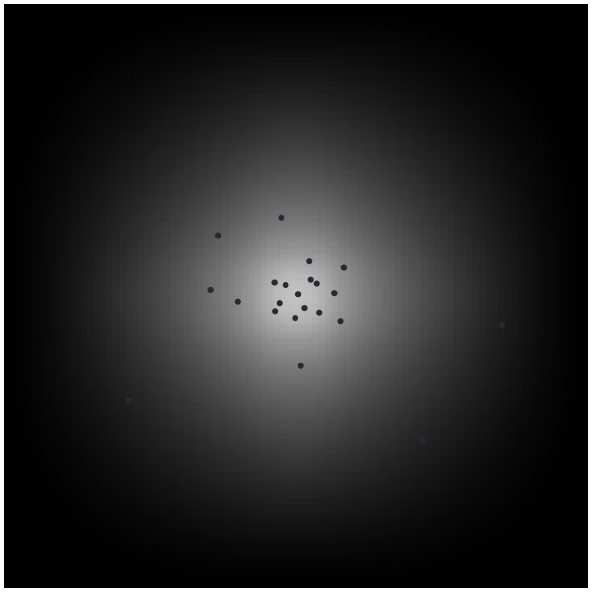
- Making wormholes from singularities ("quantum strategy"):
  - The quantum foam of a singularity contains many wormhole-like structures. Perhaps one could be expanded by throwing enough exotic matter into a black-hole singularity.
- Making wormholes without first making a singularity ("classical strategy"):
  - Severely warp and twist spacetime. It is possible, according to the Einstein field equation, but extremely hard to picture (and to illustrate), and impossible to do without distorting time as seen from all reference frames, in a manner that involves time reversal.

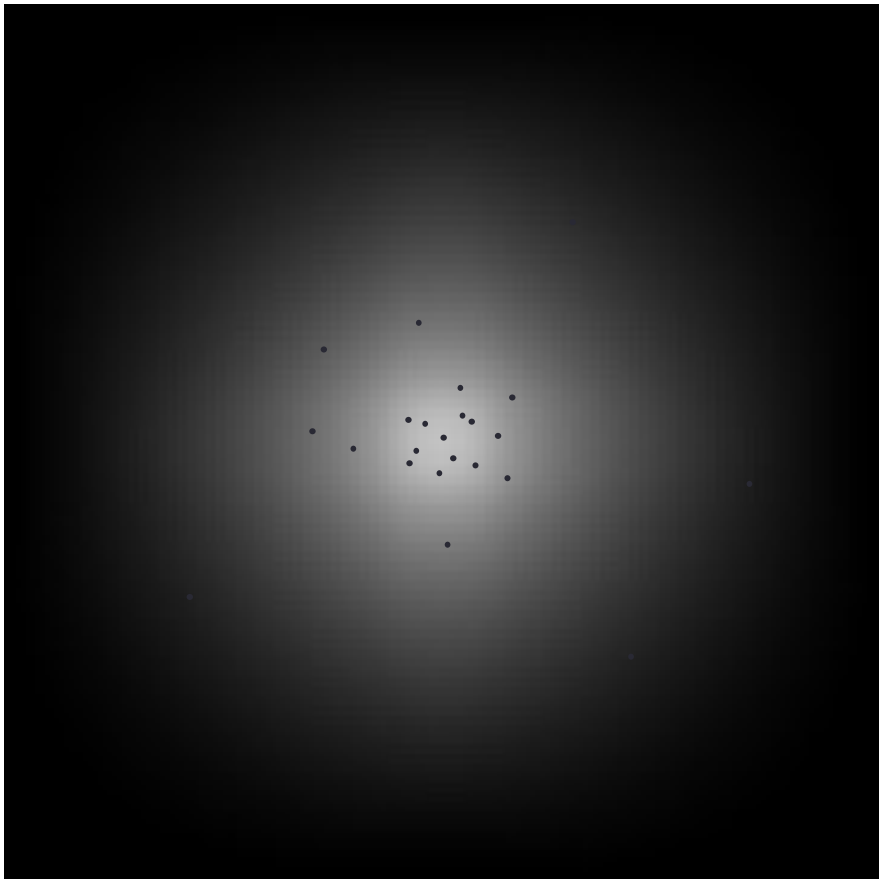
How an open wormhole might really look.

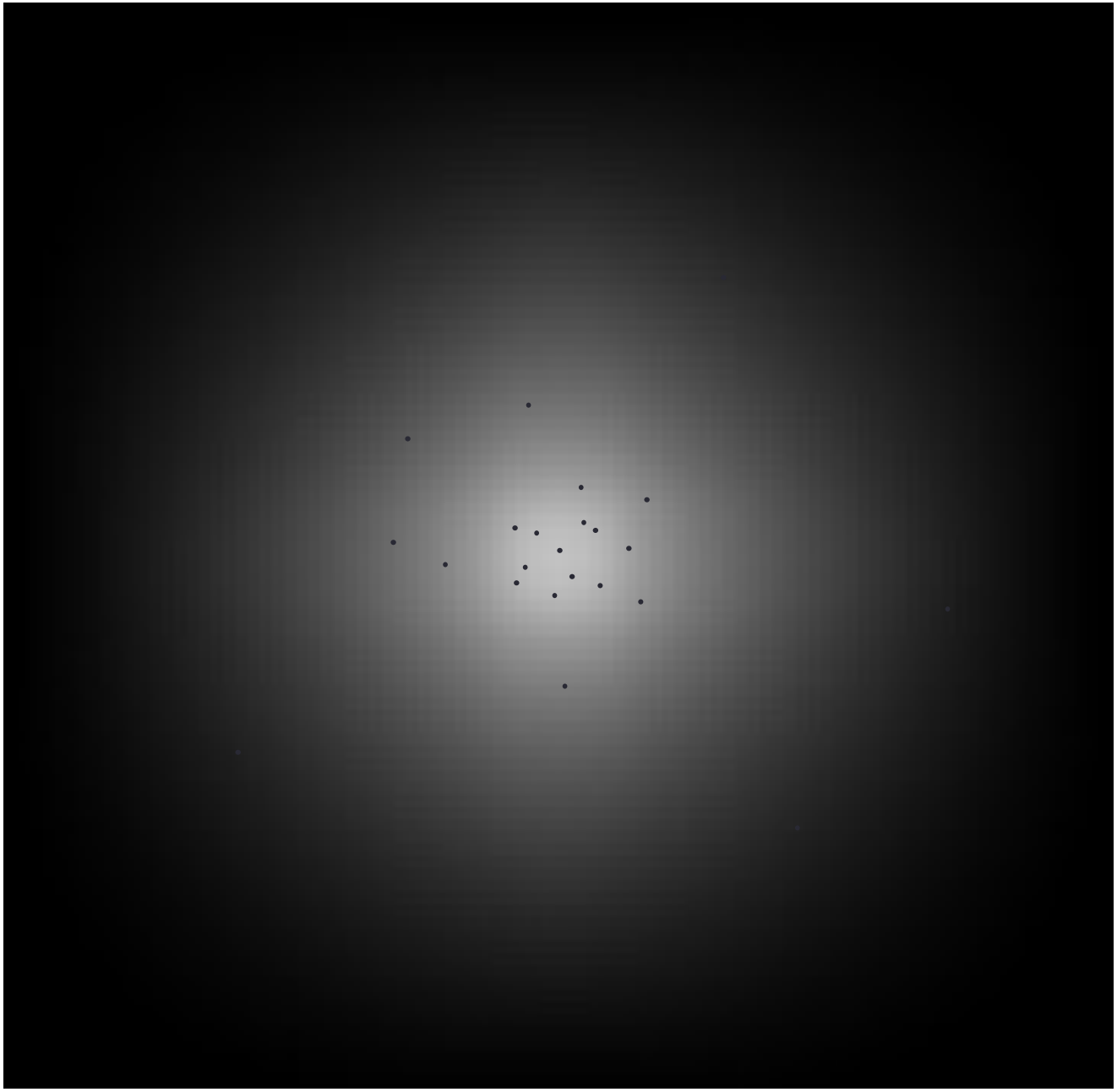


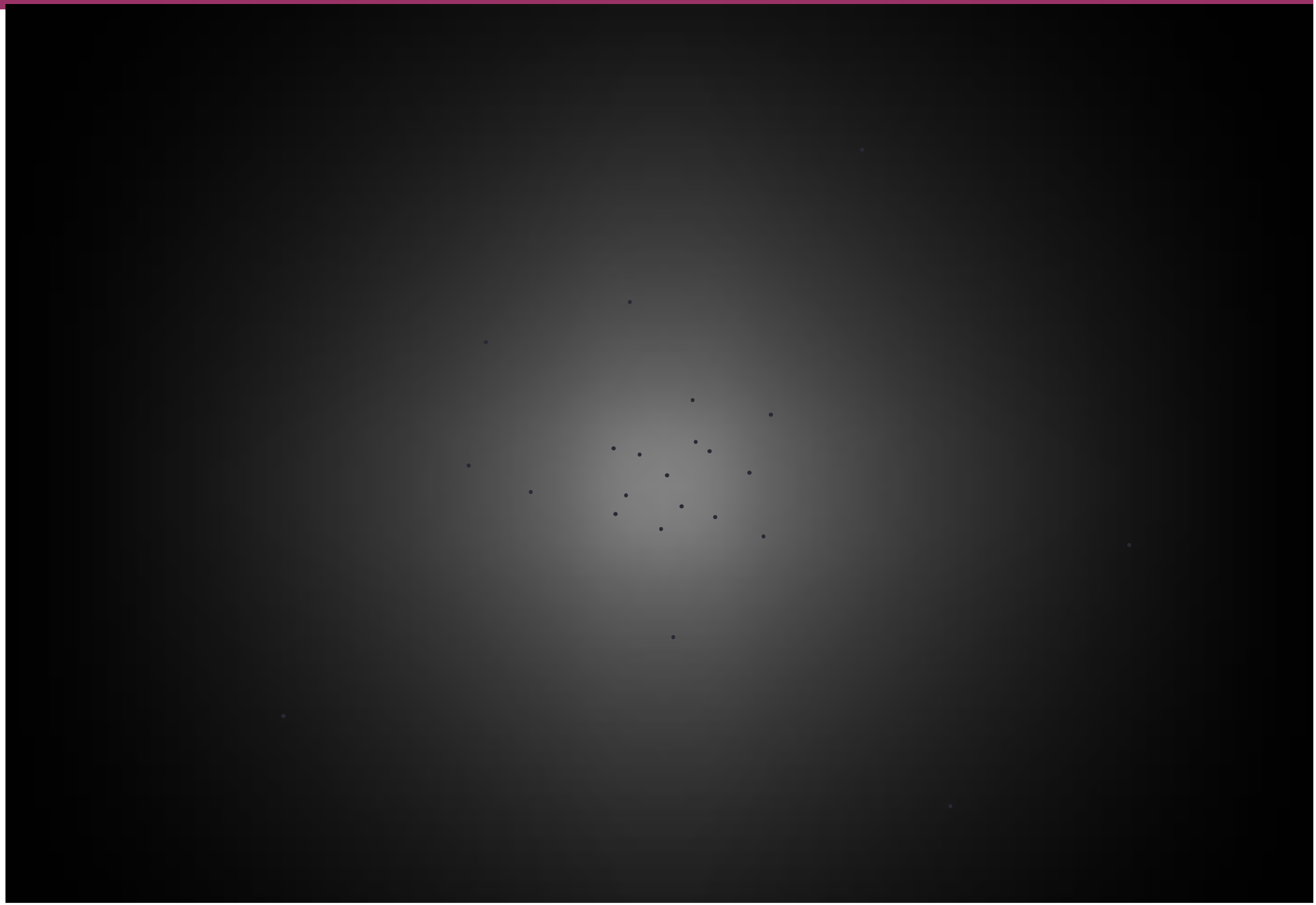
It's spherical, and like a giant globe of the sky as seen from the *other* mouth.

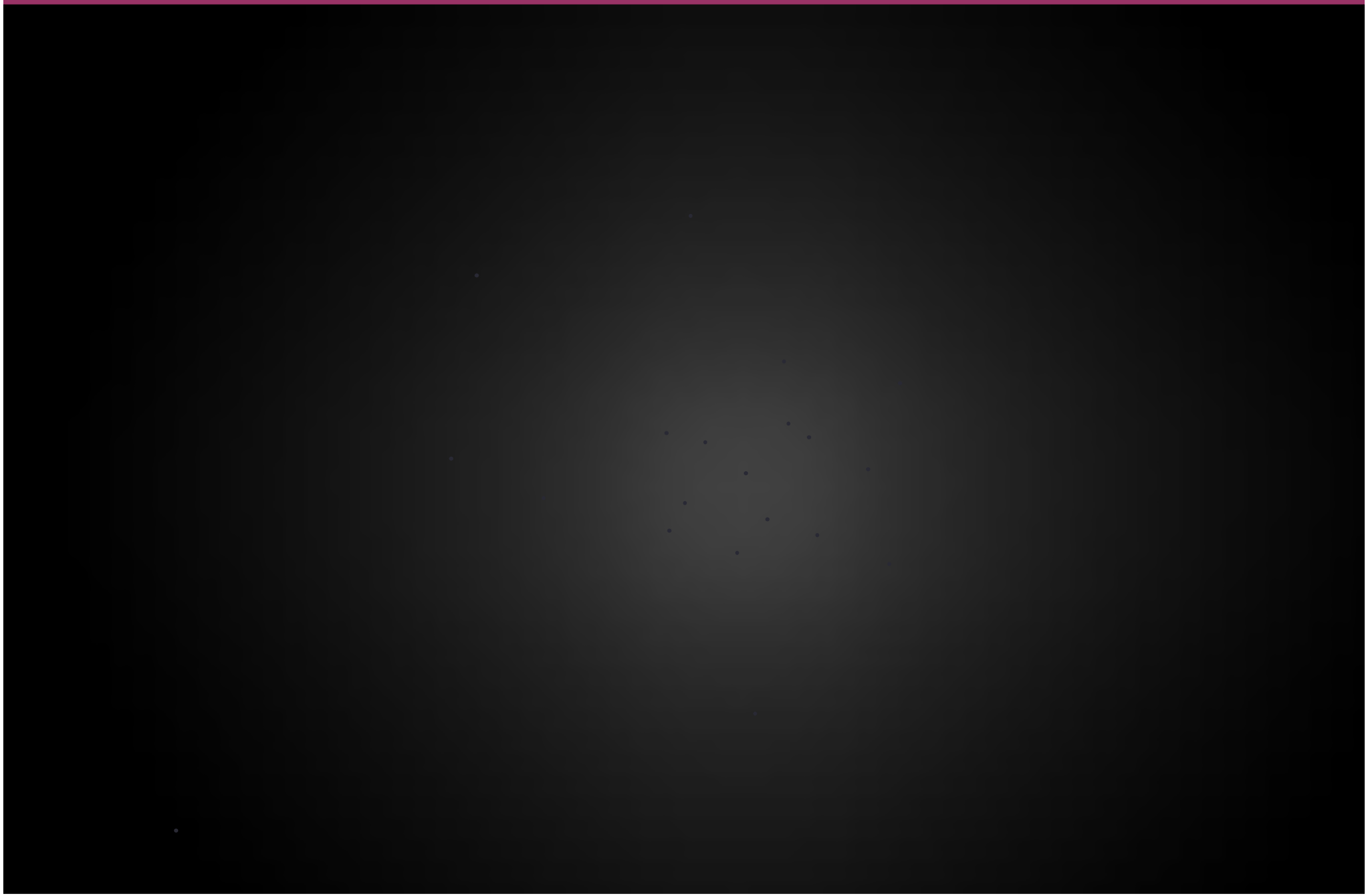
Passing through the wormhole…











…and out the other side

In your rearview mirror, you would now see a globe on which was the *initial* rear view.

Use and abuse of wormholes

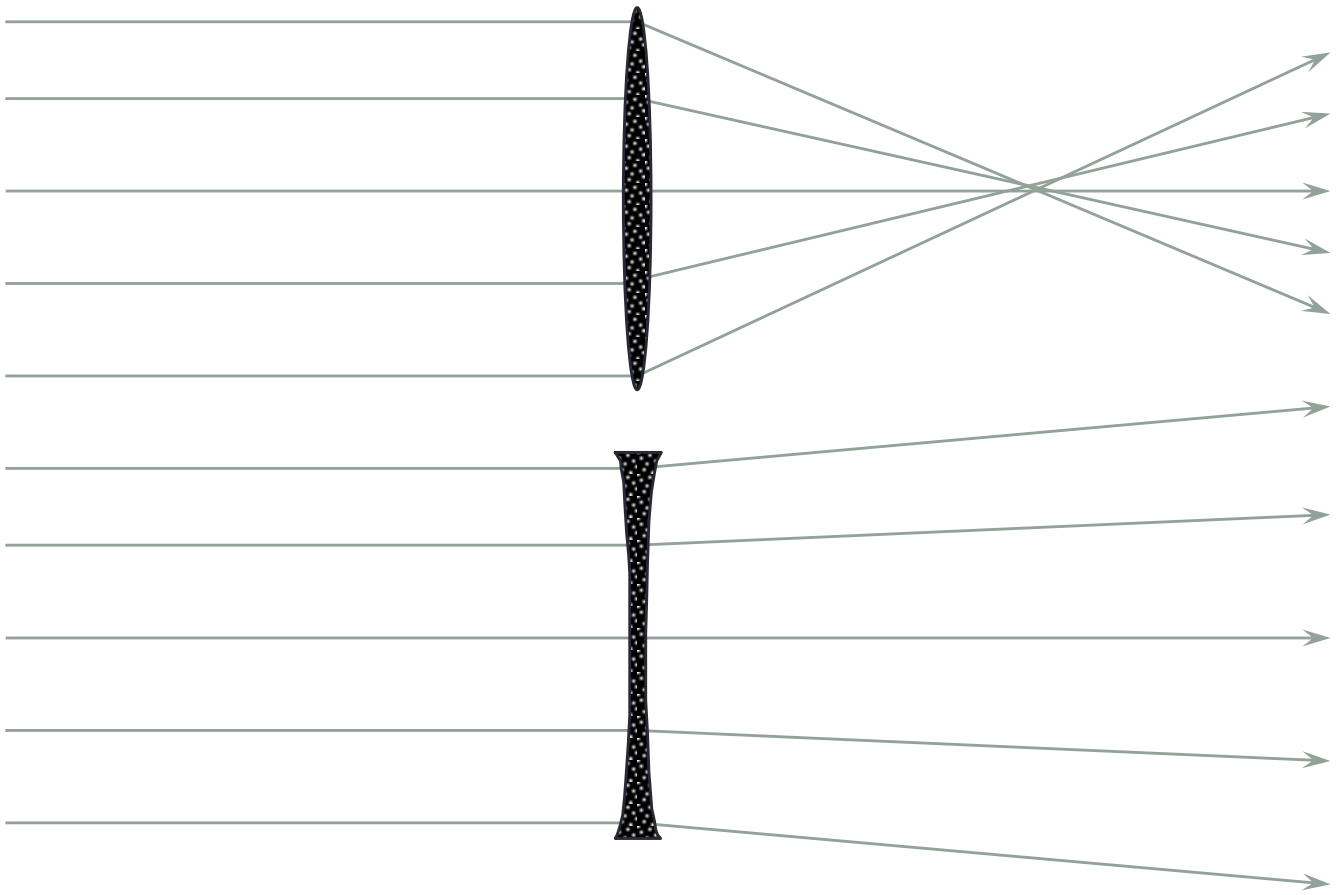
- The down side: what happens if you try to enter the wormhole to employ the shortcut?
  - You are accelerated to relativistic speeds on your way through. As a result, your energy (and mass) increase dramatically, in the view of distant observers.
  - Your mass eventually becomes large enough, halfway through the wormhole, that your own gravity warps spacetime, collapsing the wormhole onto you.
  - As your gravity “pinches off” the wormhole, singularities form again - but this time, they’re of the black hole type. Your energy is added to the black holes, and the wormhole is destroyed.

Use and abuse of wormholes (continued)

- How could we prevent the collapse of the wormhole under your gravitational influence, so you could make it through unscathed?
  - By putting exotic matter into it. Exotic matter, with its negative energy density, would be “anti-gravity”: it would warp spacetime in senses opposite to the way normal matter warps it.
  - In particular, adding exotic matter to a wormhole would tend to expand the diameter of its effective “hyperspace tunnel.”

Exotic matter in wormholes

In the sense of gravitational deflection of light, a black hole acts as a positive lens and the surrounding vacuum fluctuations act as an additional, negative lens.



Positive lens

Negative lens

Need exotic matter for stable wormhole

- Photons that enter the wormhole travelling radially inward leave it travelling radially outward without their paths crossing, like a negative lens would do; this gravitational defocussing of light can only be accomplished with negative energy-density material, since a positive energy density would have focussed them to a point before they could diverge, as a positive lens would.

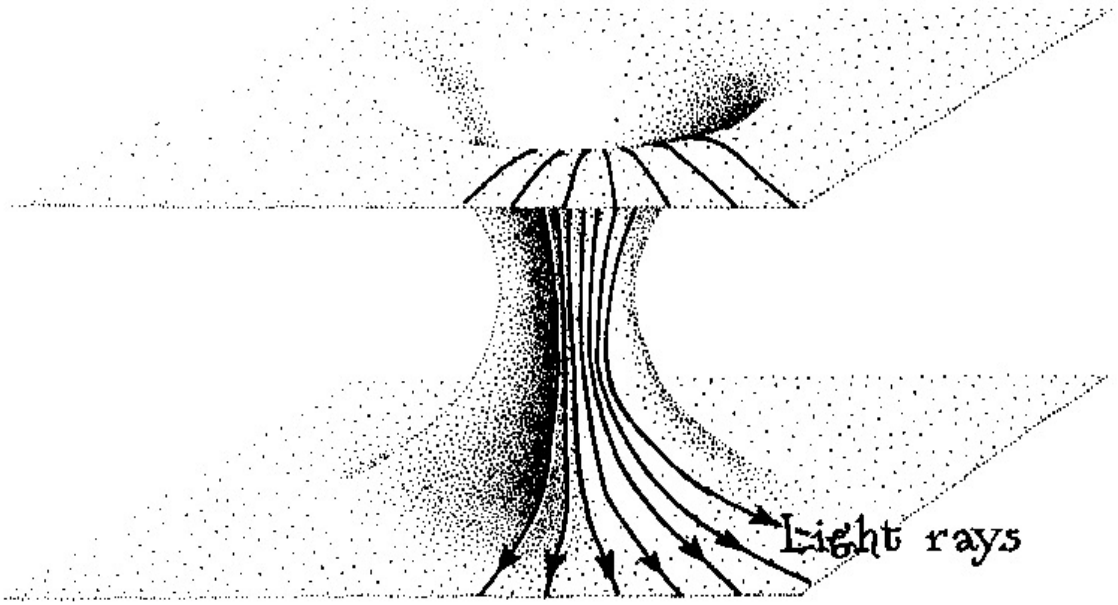


Figure from Thorne, *Black holes and time warps.*

Travel through wormhole?

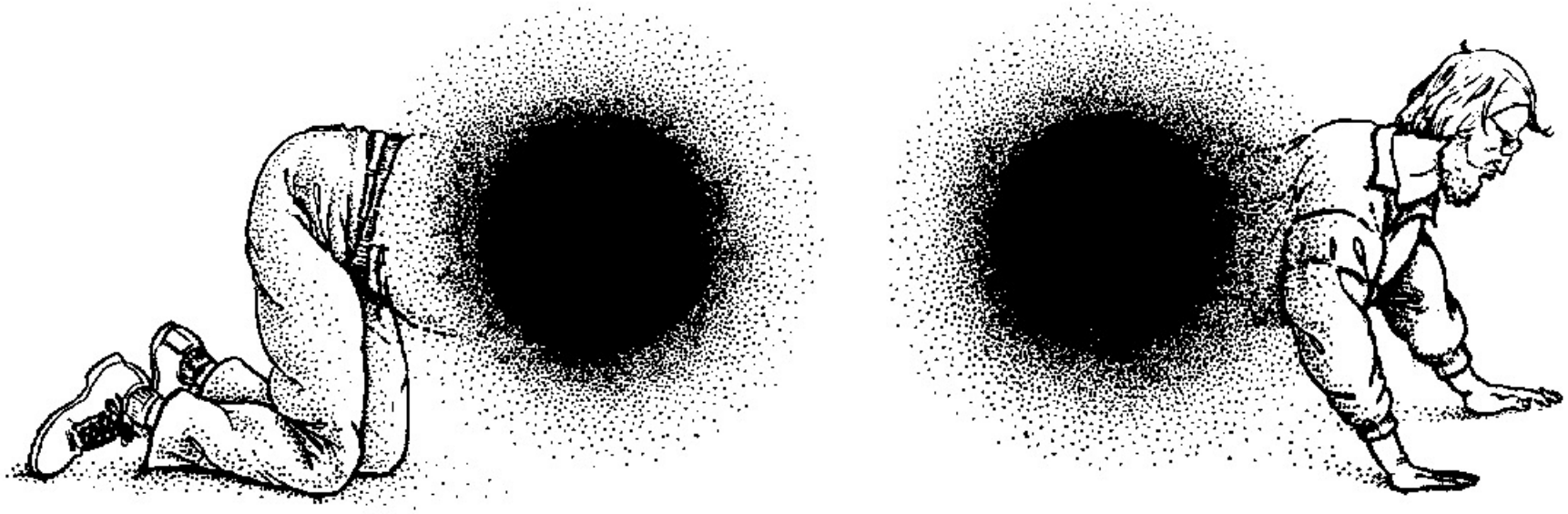


Image: Kip Thorne crawling through a wormhole. From *Black holes and time warps.*

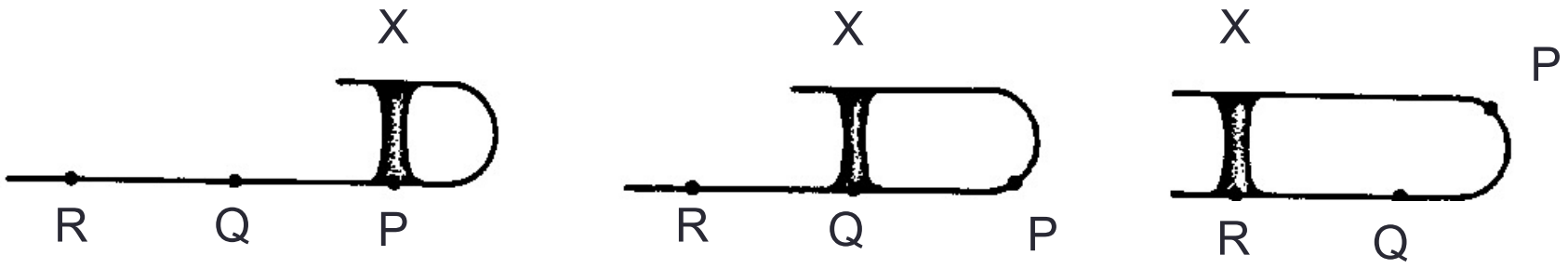
Wormholes as time machines

- How does time hook up inside a wormhole? Imagine a wormhole with **constant length in hyperspace**, but with the **two mouths moving with respect to each other in physical space**, with one of them experiencing acceleration.
  - Time dilation: clocks just outside the two mouths would appear to a distant observer to run at different speeds; the rates of time flow are different.
  - From the inside, though, the mouths appear at rest with respect to each other; the rates of time flow are the same.
  - This effect, the difference in time flows at the two mouths and the joining in the middle, could enable the use of a wormhole as a time machine, as follows...

Wormholes as time machines (continued)

Wormhole “mouths” in physical space at one instant of time

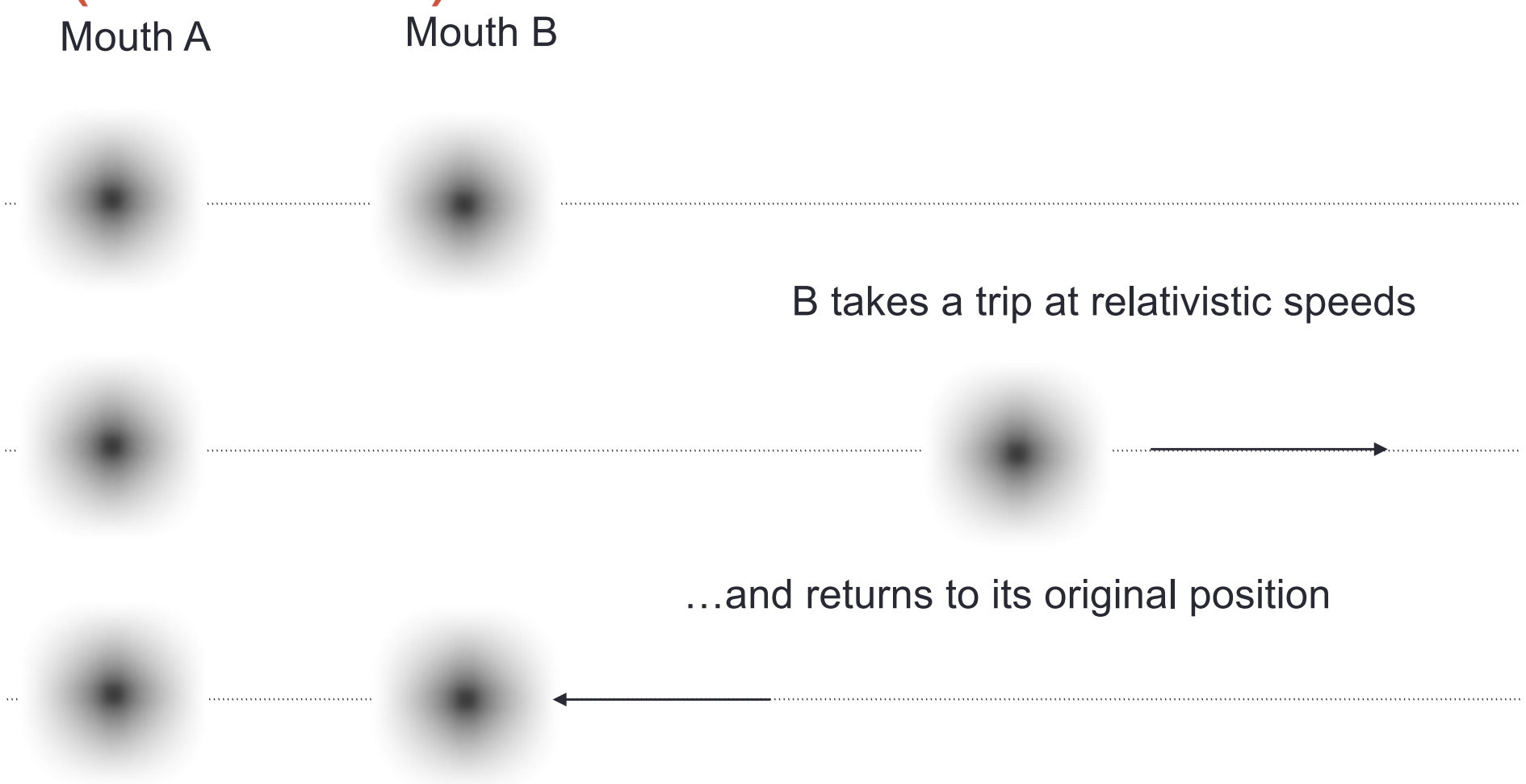
Hyperspace (at three instants of time)



How to build a wormhole time machine

- Start with a wormhole whose two mouths (called mouths A and B) are close together in space. Fix things up so that they stay the same distance apart in hyperspace.
  - In Thorne's description in the book, this is illustrated by two people reaching into each mouth to hold hands.
- Take mouth B on a trip at high speeds (approaching light speed), out a great distance, and then back to its former spot, **without ever changing the distance between the two mouths in hyperspace.**

How to build a wormhole time machine (continued)



How to build a wormhole time machine (continued)

- Because of time dilation, the trip will take a short time according to an observer travelling with mouth B, and a much longer time according to an observer who stays with the “stationary” mouth A.
- **While B is gone**, the observer at A can **travel into the future** (to the time when B returns) by passing through mouth A.
- **After B returns**, an observer at B can **travel into the past** (to the time when B left) by passing through mouth B.
- The length of time travel is thus the time lag between clocks fixed to A and B during B’s trip, and is thus adjustable by adjusting the details of the trip.
- Travel between arbitrary times is not provided!

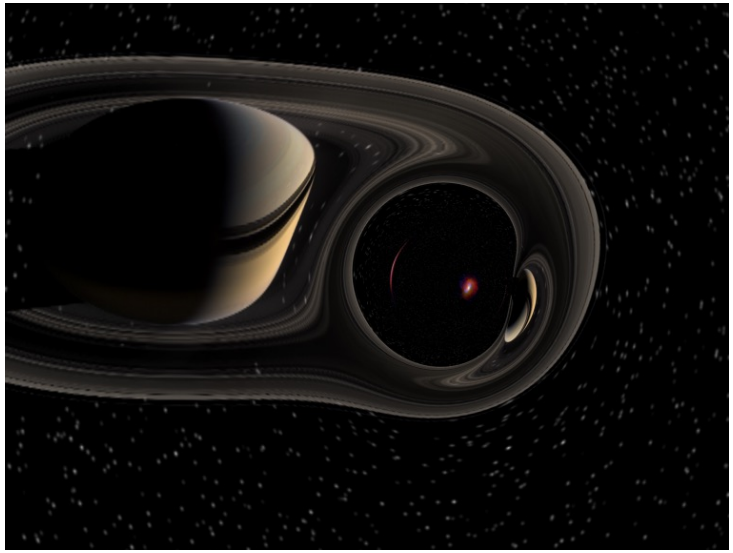
Odd features of time travel

- **Paradoxes such as the "grandfather paradox" come up!** One could use a time machine, for example, for travelling back through time and killing one's grandfather.
- Does physics prevent one from being born and travelling back through time in the first place?
  - **Maybe**. How is it that one can start with laws of physics like the Einstein field equation, that have cause and effect built in, and derive from them violations of cause and effect?
  - **Maybe not**. What about quantum mechanics? Vacuum fluctuations, for instance, have no "cause." If quantum behavior (associated with singularities) is inherent in the wormhole, one could still exist after committing paradoxical matricide.

How time travel would not work

- A great movie... but things change after Marty McFly goes back and forth in time
- This is thus a self-inconsistent timeline

How time travel might work

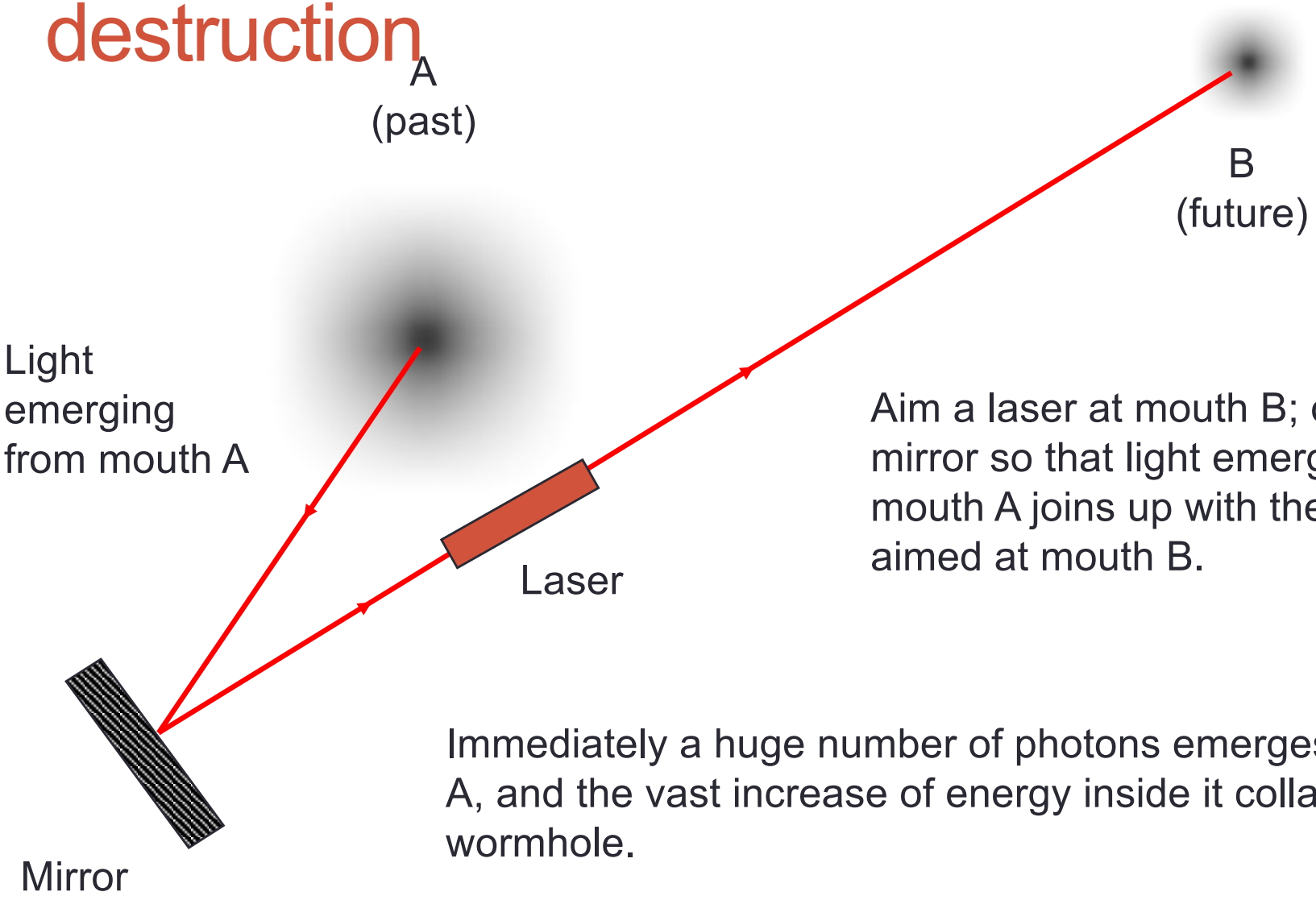


- (can you identify the two scenes?)
- Time travel may or may not be possible, but self-consistency is the key.
- If it happened once, and you travel back and forth in time, it has to happen again

Alas, it may be impossible to build a stable wormhole time machine

- Geroch, Wald, and Hawking on self-destruction of wormhole time machines:
  - Light leaving the origin during B's trip, and entering mouth B as it is returning, can travel backwards in time, emerge from A, and meet itself in the act of leaving.
  - It can do this as many times as it likes, even an infinite number of times.
  - Since light can interfere constructively (all the peaks and troughs of the light wave lining up), a large positive energy density could be generated in the wormhole, which would collapse it.
  - This process could take as little as 10^{-95} seconds in the frame of reference of mouth A.

A recipe for wormhole time-machine destruction



Aim a laser at mouth B; orient mirror so that light emerging from mouth A joins up with the beam aimed at mouth B.

Immediately a huge number of photons emerges from mouth A, and the vast increase of energy inside it collapses the wormhole.

Problems with stable wormholes, continued

- It's also possible for this to happen with light created by **vacuum fluctuations**!.
  - Since light has *wave* properties too, the probability that virtual photons from near A to travel to B and re-emerge from A pointed again at B is not zero, even if there is nothing to aim the photons that way.
- The interference may not be constructive, though, because the wormhole tends to defocus the light in the manner of a negative lens; therefore we do not know whether this is a fatal objection.

Summary of wormholes

- These are legal solutions of Einstein's equations
- They probably pop in and out of quantum froth all the time
- But to keep them open you need "exotic matter", which is matter that has a negative(!!!) energy density
- There are ways you can do this, and dark energy has similarities, but we don't know whether it is possible even in principle to produce a stable wormhole
- Wormhole⇔time travel; self-consistency is the key!