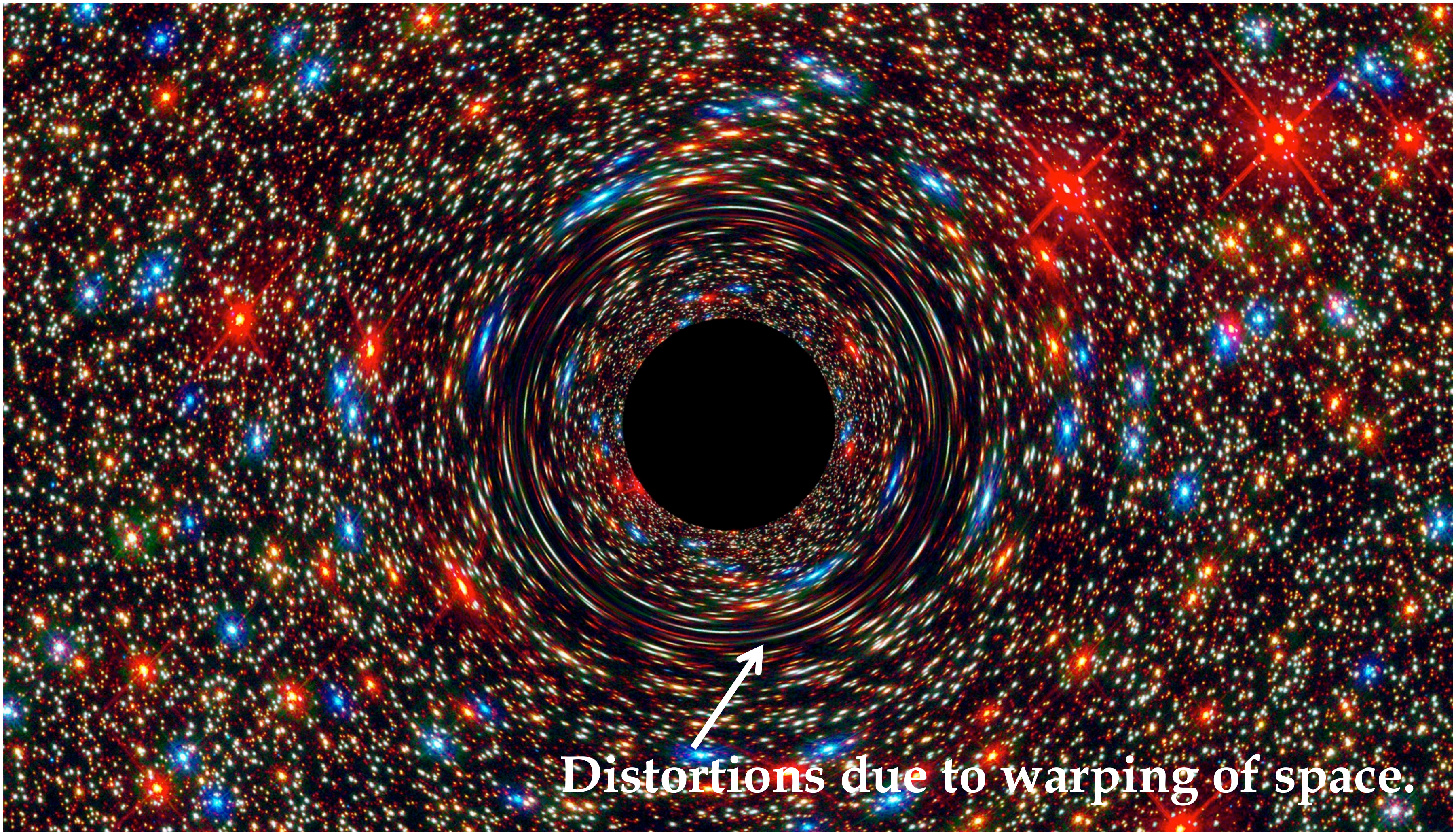
Today in Astronomy 102: Wormholes

- Wormholes, and how to construct one using black holes.
- Wormhole maintenance: how objects like the StarTrek: DS9 wormhole might work.

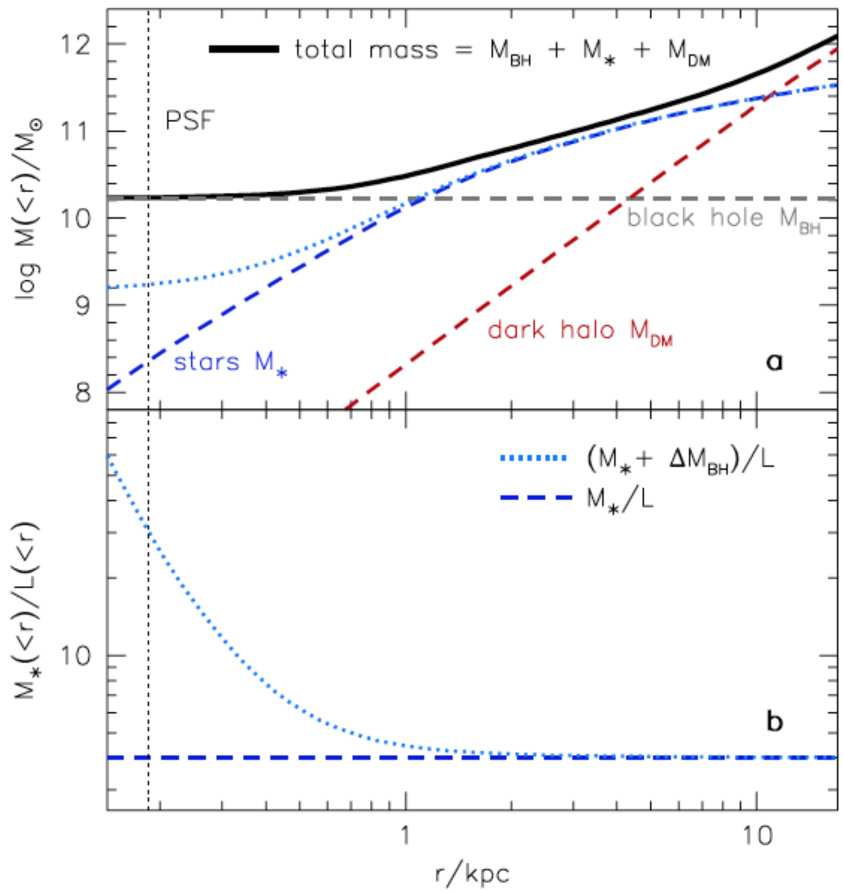
Hypothetical spacecraft about to enter a hypothetical wormhole (NASA Glenn Research Center).

Behemoth Black Hole Found in an Unlikely Place

http://www.nasa.gov/feature/goddard/2016/behemoth-black-hole-found-in-an-unlikely-place



Measuring the black-hole mass by observing orbital motion.



Extended Data Figure 5 | The enclosed mass of NGC 1600. a, The enclosed stellar mass (M_*, blue), dark-halo mass (M_{DM}, red), black-hole mass (M_{BH}, grey) and combined total mass (black) obtained in our model from the smallest resolved radius (point-spread-function, PSF, size) out to 20 kpc (Mitchell IFU size). **b**, An illustration of the excessive M_*/L gradient (dotted pale blue curve) that would be required for a hypothetical population of unresolved central dwarf stars to explain 10% of NGC 1600's measured M_{BH}. The stellar mass-to-light ratio would have to increase by about a factor of ten (dotted pale blue curve) over our best-fit constant value (dashed blue curve). Observations of other galaxies suggest that extreme populations of dwarf stars can increase M_*/L by a factor of up to three.

Deficit of stars in the center.

- Lower luminosity elliptical galaxies have rising light profiles towards the center of the galaxy.
- NGC 1600 shows a deficit of stars in the central region.
- Similar observations are made for other galaxies with massive black holes.

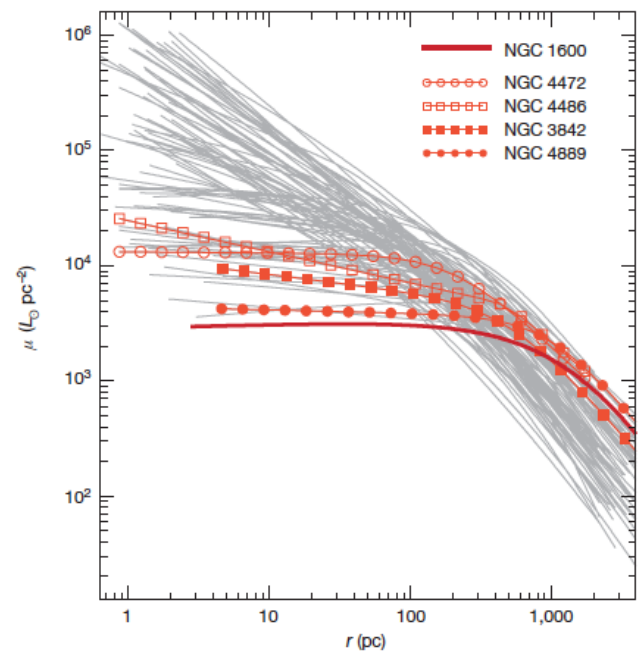


Figure 2 | Central stellar light profiles for NGC 1600 and for a sample of other core and coreless elliptical galaxies. Surface brightness profiles (in the V-band) are shown for a sample of galaxies, on the basis of HST observations[13] up to a distance of 100 Mpc from Earth. NGC 4889, at 102 Mpc, is included because its black-hole mass has been measured[2]. μ is the surface brightness and r is the galactic radius at which the brightness was measured. Lower-luminosity elliptical galaxies typically have rising light profiles towards the galactic centres (steep grey curves), whereas NGC 1600 and other very massive elliptical galaxies often exhibit a marked deficit of stars in the central region (red curves). Highlighted are the brightest galaxies in the Leo Cluster (NGC 3842) and the Coma Cluster (NGC 4889), and the brightest (NGC 4472) and central (NGC 4486 or M87) galaxies of the Virgo Cluster. The stellar core in NGC 1600 (dark red curve) is the faintest known among all galaxies for which dynamical M_{BH} measurements are available.

Core radius vs black-hole mass.

- The larger the core radius, the larger the black hole mass.
- The black hole in NGC 1600 has a Schwarzschild radius of 5×10^{10} km.
- The core radius of NGC 1600 is 4×10^{16} km.

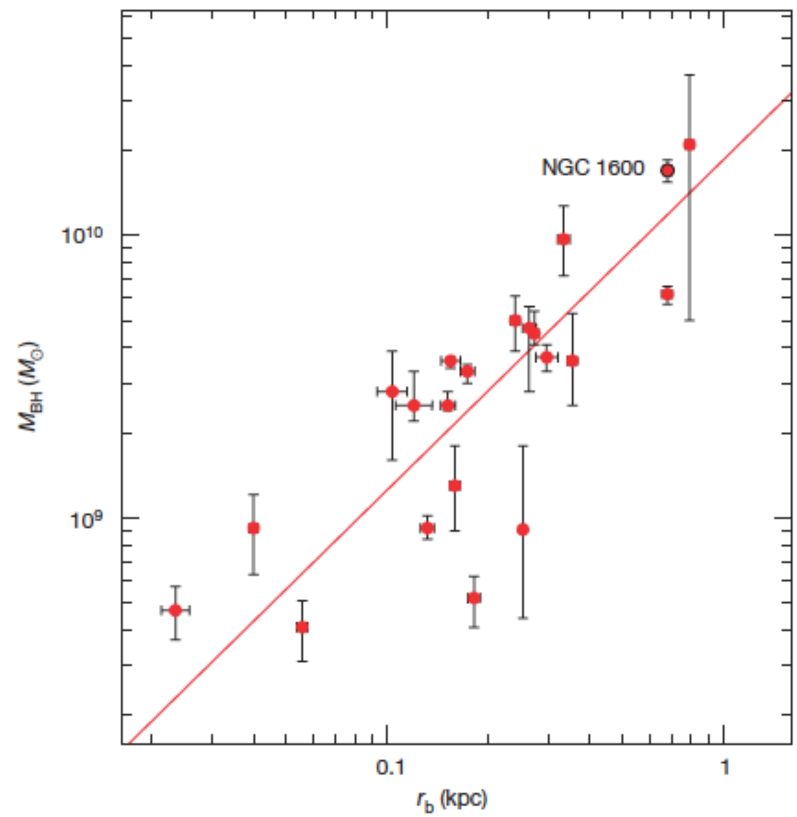


Figure 4 | Black-hole mass and galaxy core radius. The black-hole mass, M_{BH}, is plotted against the core radius, r_b, for the same sample of galaxies as in Fig. 3 (and with 1σ error bars). The straight line shows our best fit for a constant-exponent power-law relation between M_{BH} and r_b: $\log_{10}(M_{BH}/M_\odot) = (10.27 \pm 0.51) + (1.17 \pm 0.14)\log_{10}(r_b/\text{kpc})$. The intrinsic scatter of this relation is $\epsilon = 0.29 \pm 0.07$.

Back to wormholes.

It is easy to get distracted by new observations.

Wormholes

Wormholes are solutions to the Einstein field equation that involve two mass-density singularities. A wormhole can be thought of as a special combination of two black holes.

By special, we mean that the **interiors of the two black holes are connected** under some circumstances.

- ❑ Remember how strongly warped space is, near and within a black hole horizon: a lot of space is contained therein, and if it weren't so strongly curved it could reach a long way – and, if it reaches inside another black hole…
- ❑ Or, if you prefer the hyperspace paradigm (as we do in this class): black holes that are distinct in physical space can **overlap in hyperspace.**

A concrete example may show better what we mean…

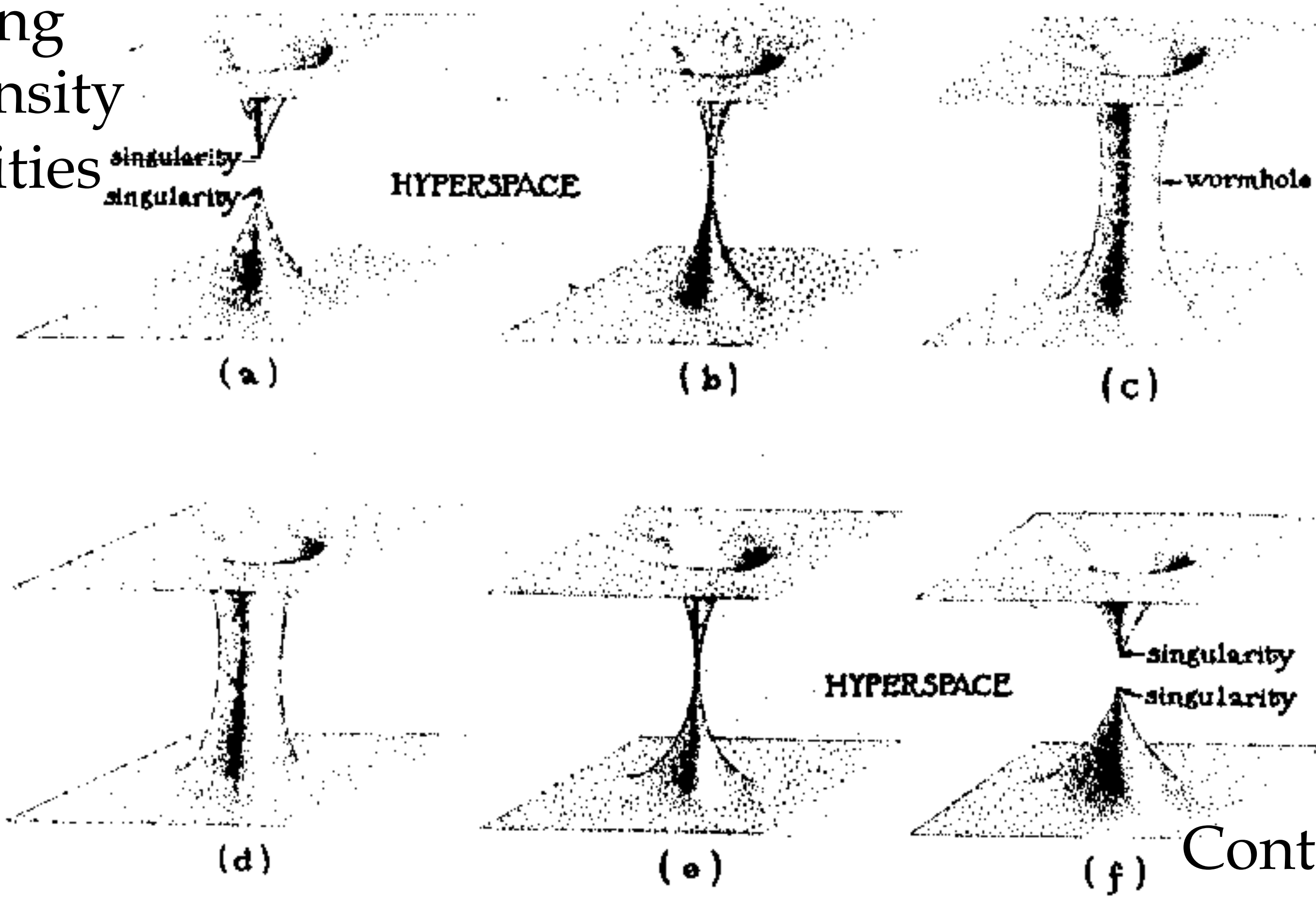
Construction and destruction of a wormhole

Start with two black holes that overlap in hyperspace, each in a configuration in which the mass-density singularity is an expanding **singularity** (time flows out of the singularity; this is sometimes, but inconsistently, called a "white hole").

- According to our present (incomplete) understanding of quantum gravity, two such singularities may "unwarp" each other to produce a "tube" of continuous paths through hyperspace between the two black holes.
- **The "unwarping" may even eliminate the horizons!**
- This tube through hyperspace is the wormhole. It wouldn't look like a tube in *physical* space, though; each mouth would still look spherical from the outside.
  (We will describe in a little more detail *how* it looks in physical space in a little bit.)

Construction and destruction of a wormhole (continued)

Expanding mass-density singularities

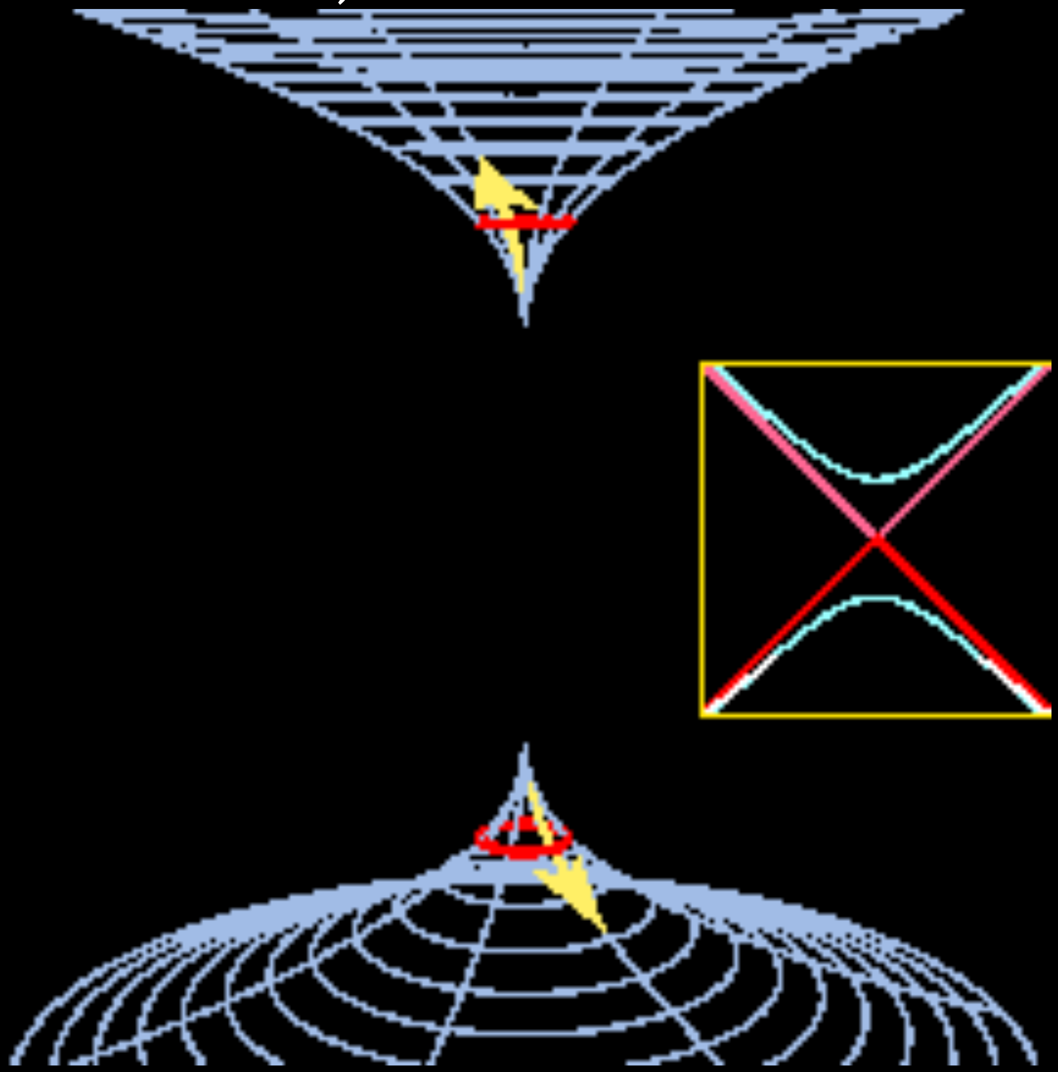


Contracting mass-density singularities

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

Construction and destruction of a wormhole (continued)

Like the previous page, but animated. (From Andrew Hamilton's wormhole pages, which can be found here.)

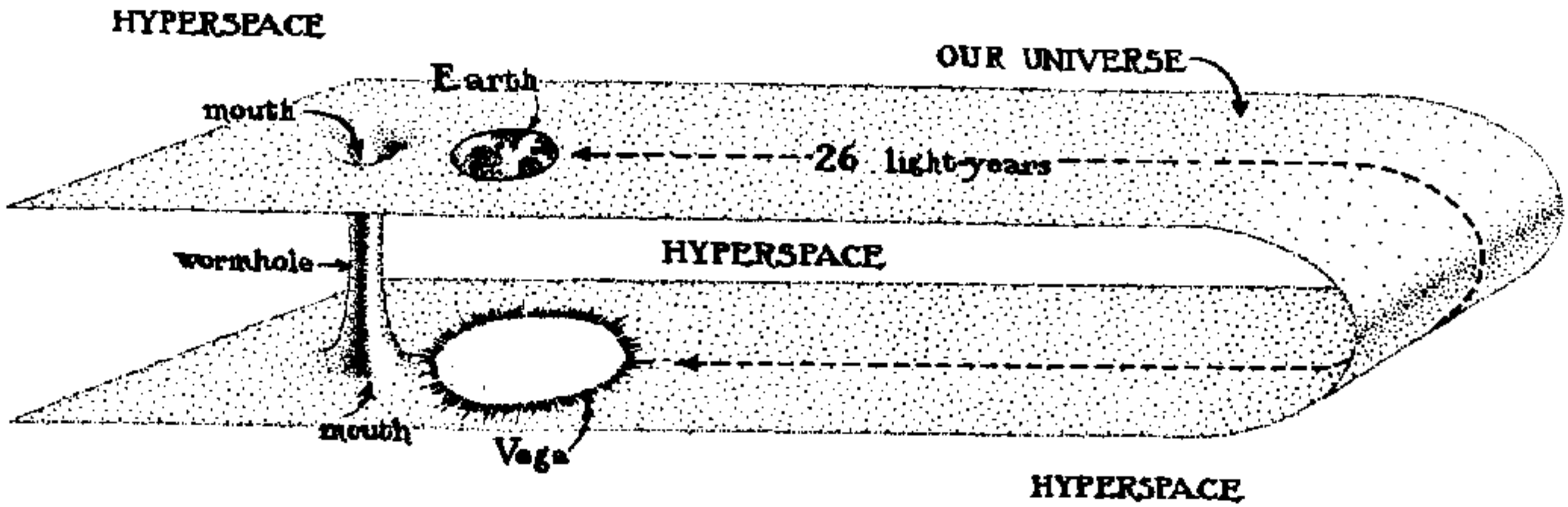


Construction and destruction of a wormhole (continued)

- Since the mass-density singularities were of the expanding type (time flows out in both hyperspace directions), the diameter of the wormhole initially expands with time.
  - **Practical upshot**: the paths through hyperspace become somewhat less strongly warped: there would be decreasing gravitational forces and tides on bodies that found themselves there, while it expands.
- It is possible for the path through hyperspace to be short, while the distance between the singularities is very large, measured in "real" spacetime.
  - **Practical upshot:** the wormhole can be a shortcut through spacetime. (Of course, it could also be longer than the straight path through regular spacetime…)

A hyperspace shortcut *via* a wormhole

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



From Thorne, *Black holes and time warps*

Other methods of wormhole construction

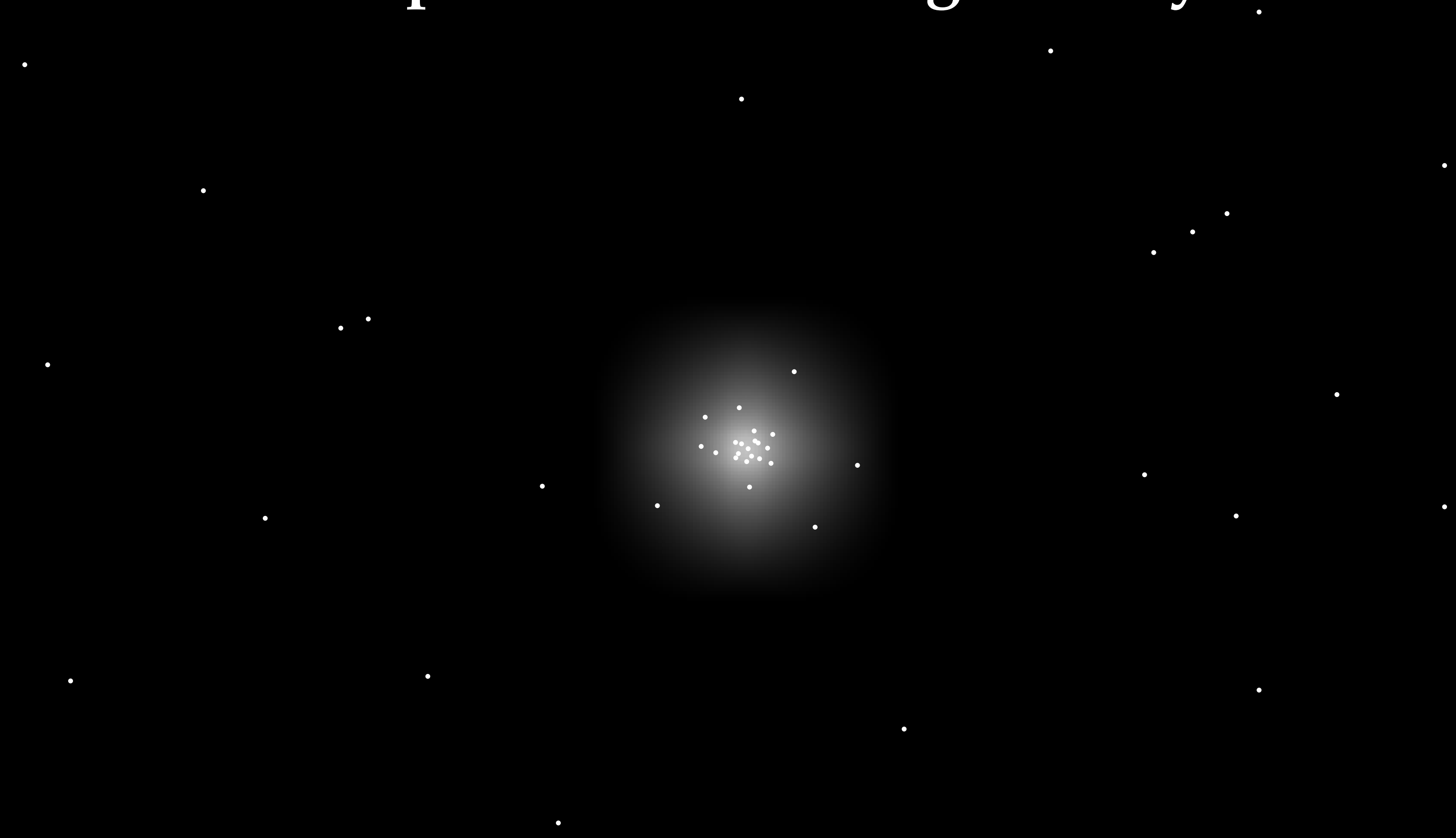
Making wormholes from mass-density singularities ("quantum strategy"):

- The quantum foam of a mass-density singularity contains many wormhole-like structures. Perhaps one could be expanded by throwing enough exotic matter into a black-hole mass-density singularity.

Making wormholes without first making a singularity ("classical strategy"):

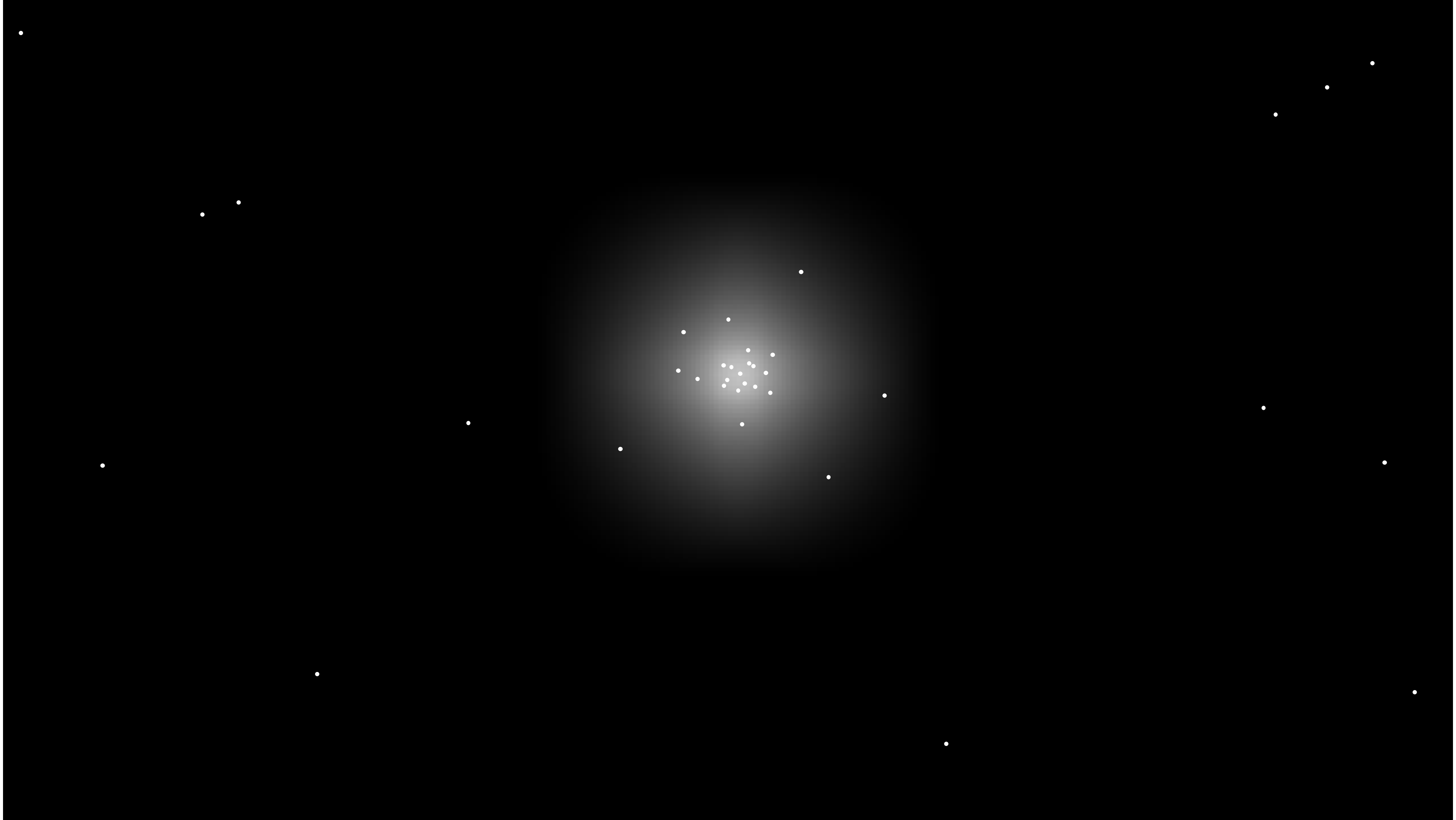
- Severely warp and twist spacetime. It is possible, according to the Einstein field equation, but extremely hard to picture (and to illustrate), and impossible to do without distorting time as seen from all reference frames, in a manner that involves time reversal.

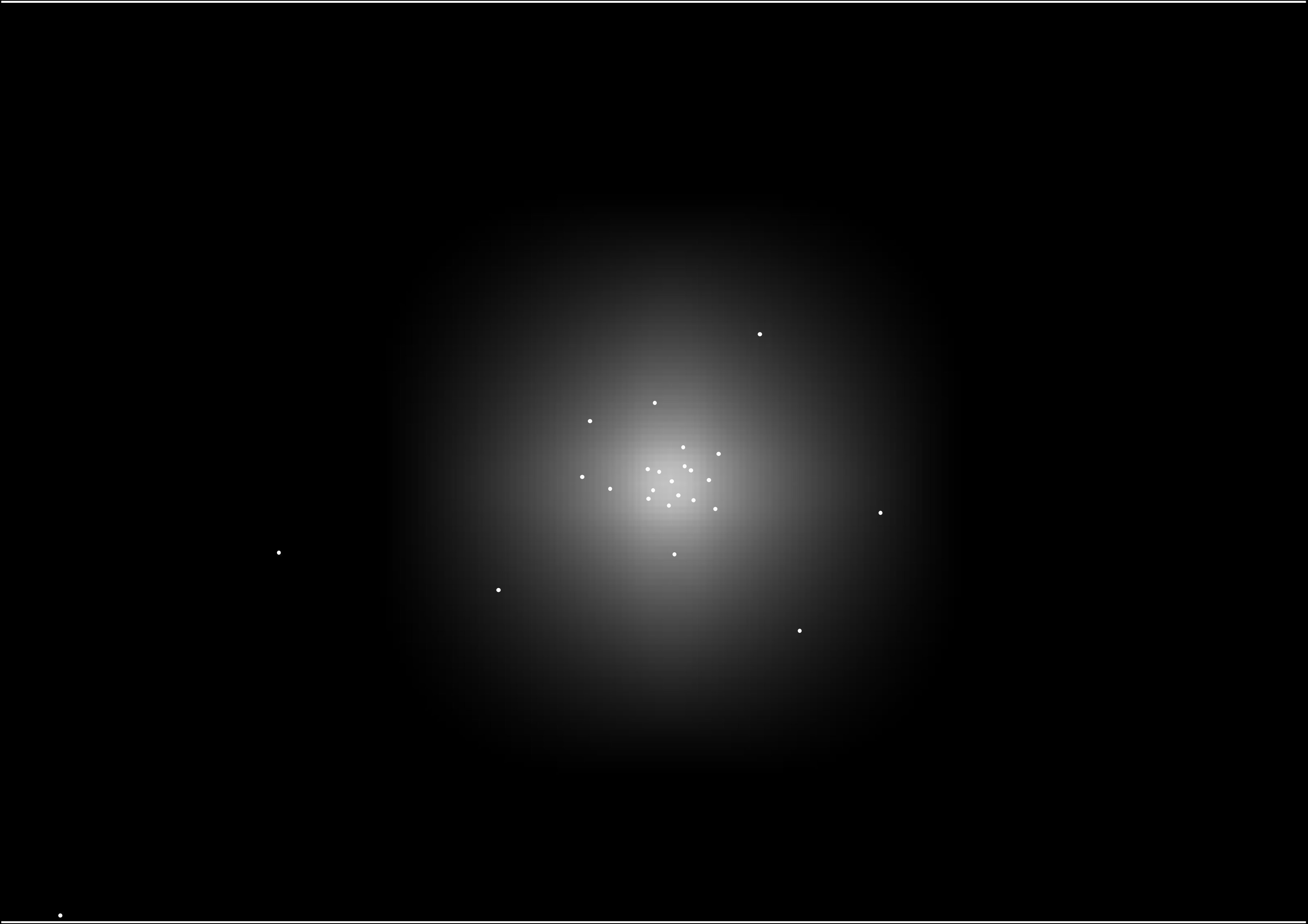
How an open wormhole might really look.

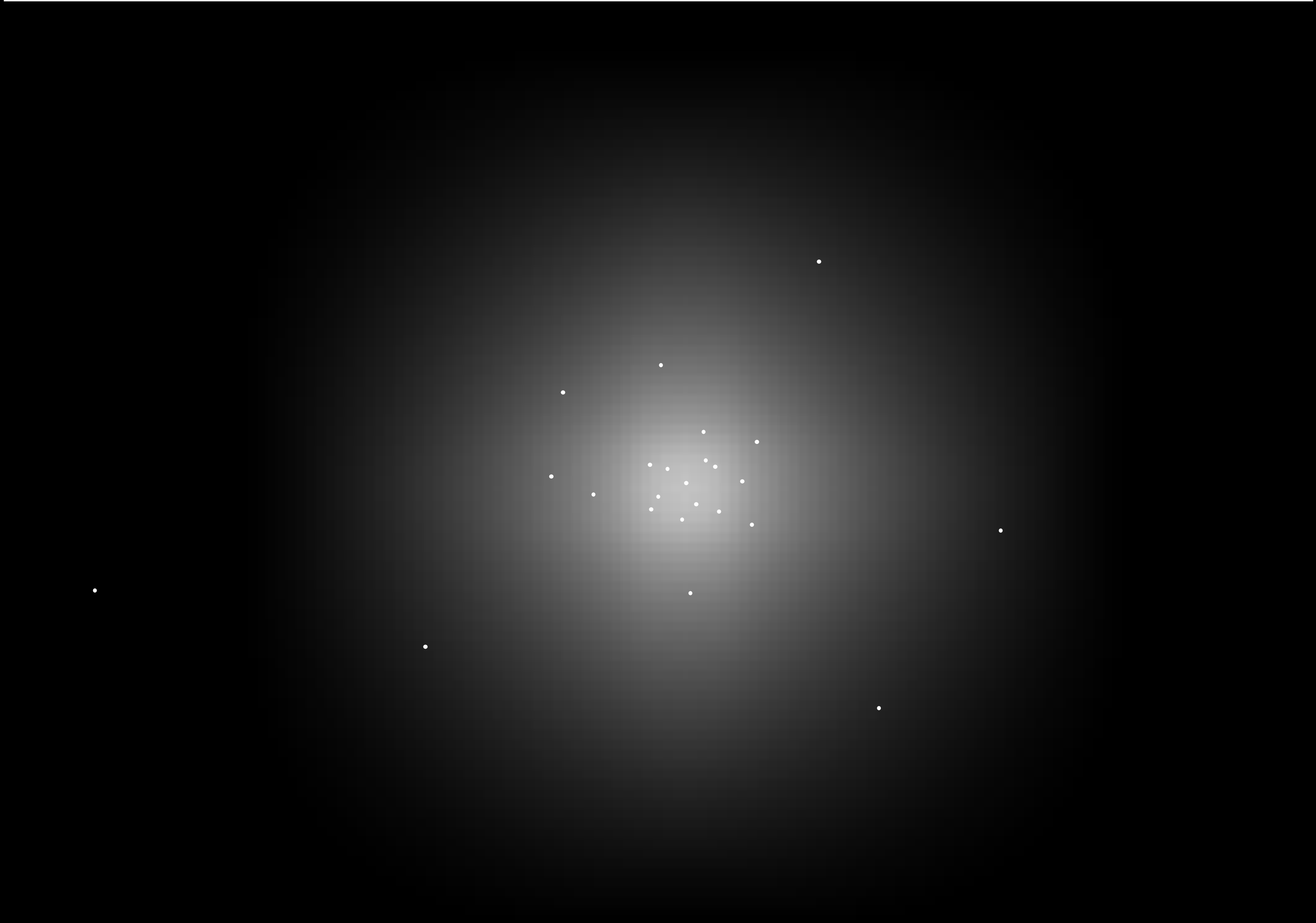


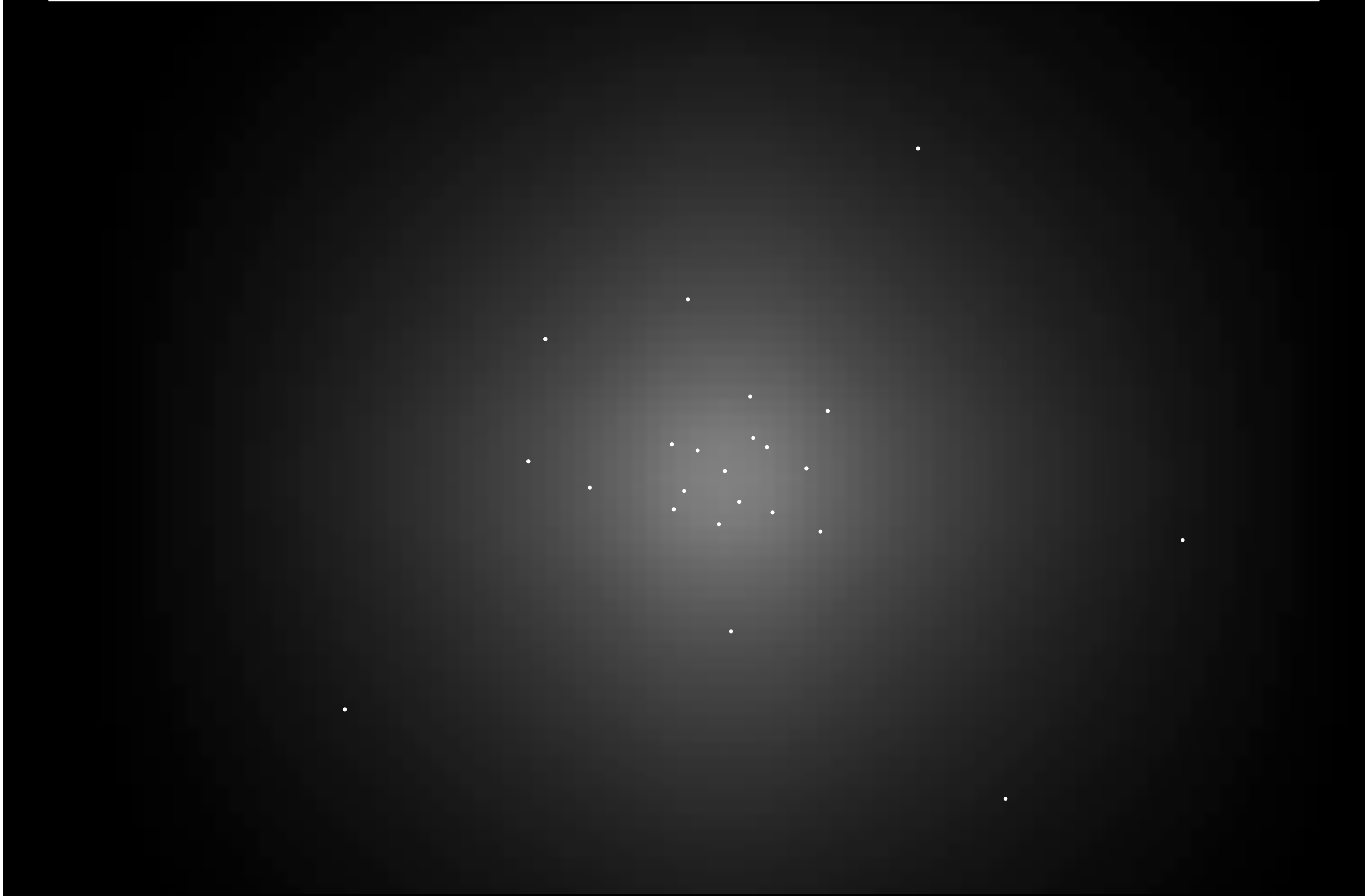
It's spherical, and like a giant globe of the sky as seen from the *other* mouth.

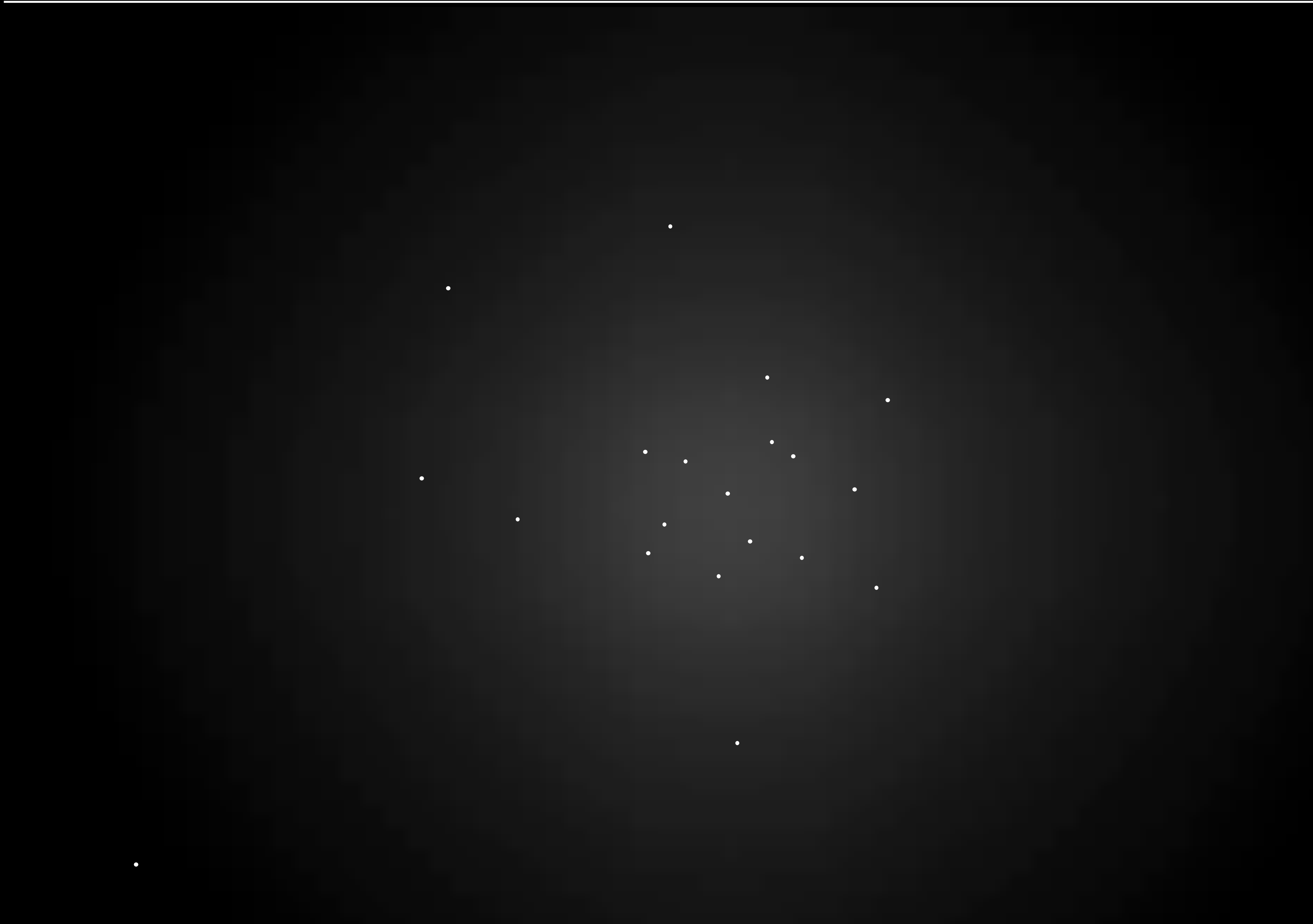
Passing through the wormhole…



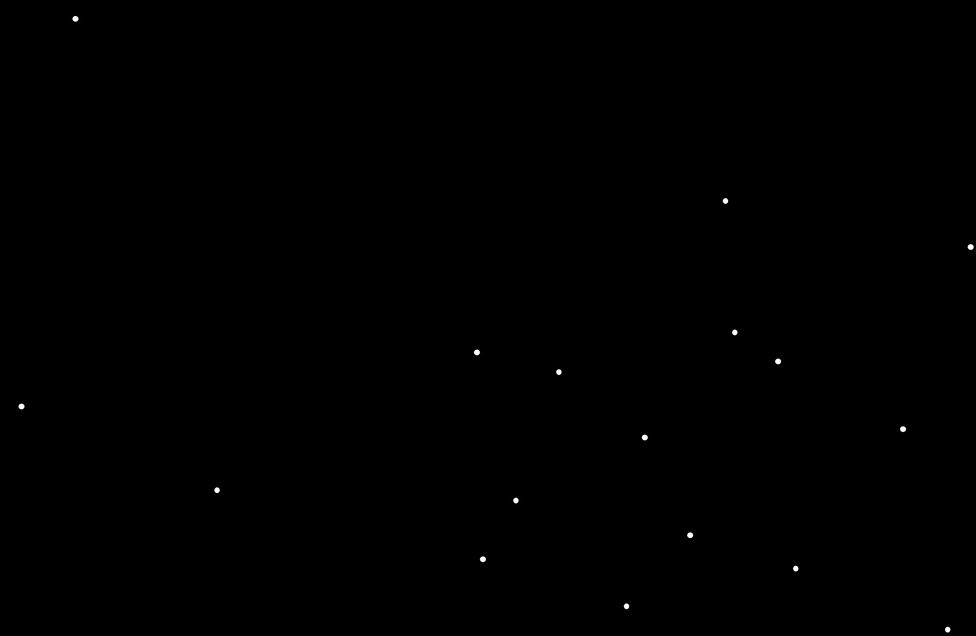








…and out the other side



In your rearview mirror,
you would now see a
globe of the sky seen from
the mouth you entered.

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 rest frame of the wormhole.
- 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 (and you are, too).

Use and abuse of wormholes (continued)

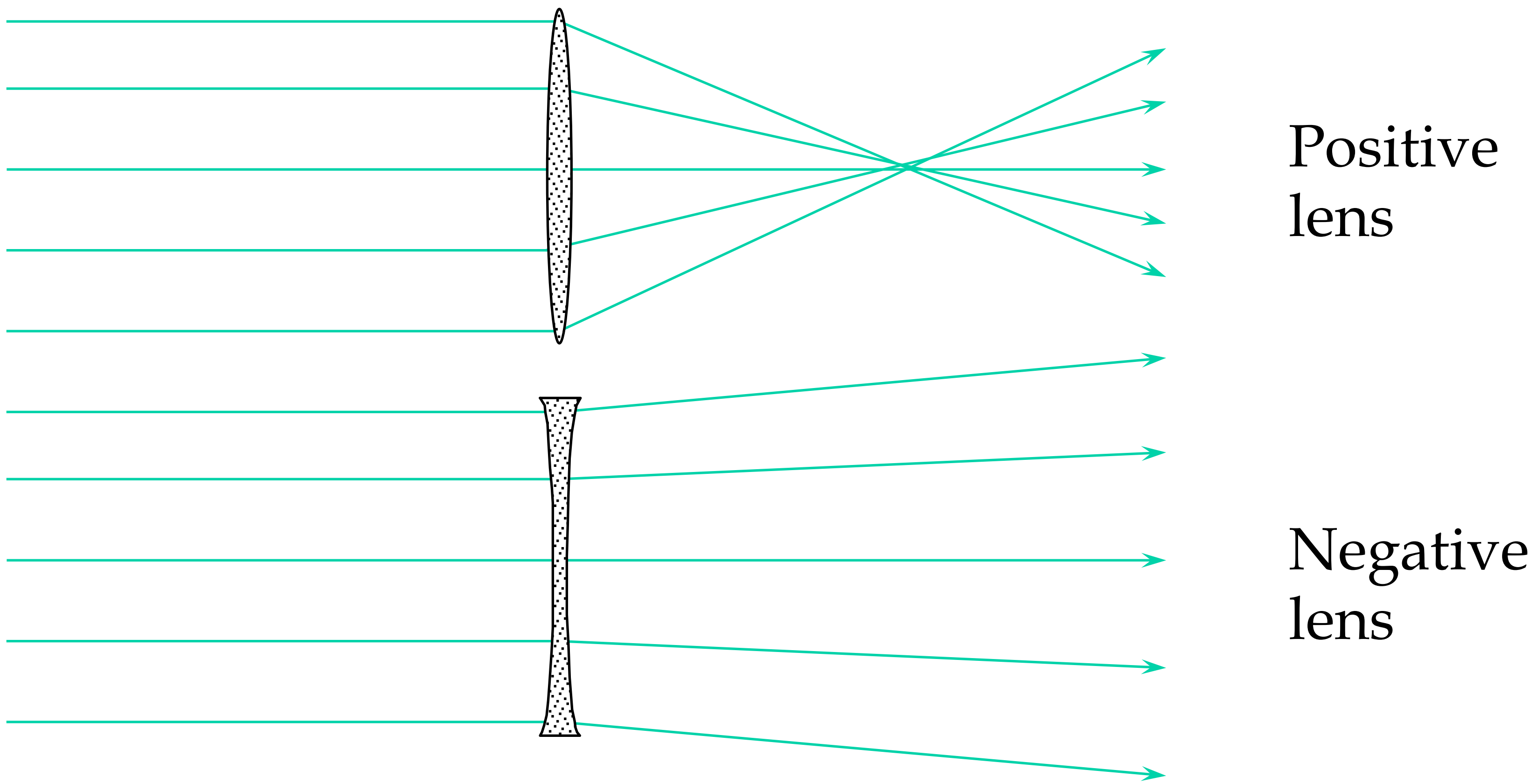
How could we prevent the collapse of the wormhole under your gravitational influence, so you could make it through unscathed?

- 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."

Recall the calculation of the effect on gravitational deflection of light by the (exotic) vacuum fluctuations near a black hole's event horizon (lecture 19).

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.



If a wormhole is stable, it must contain exotic matter

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.

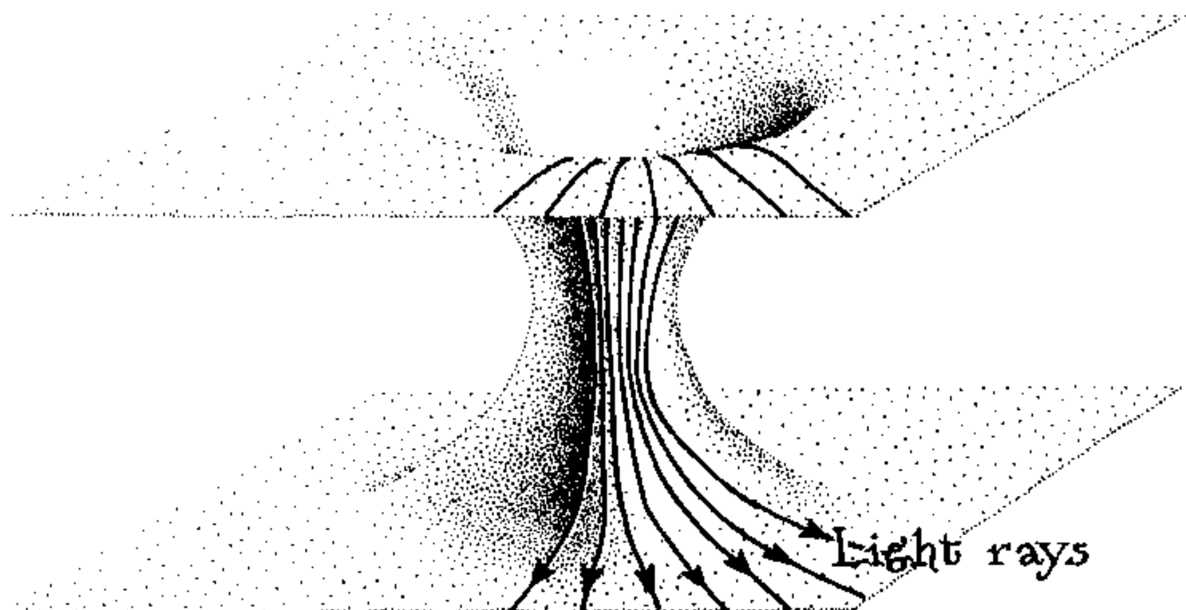
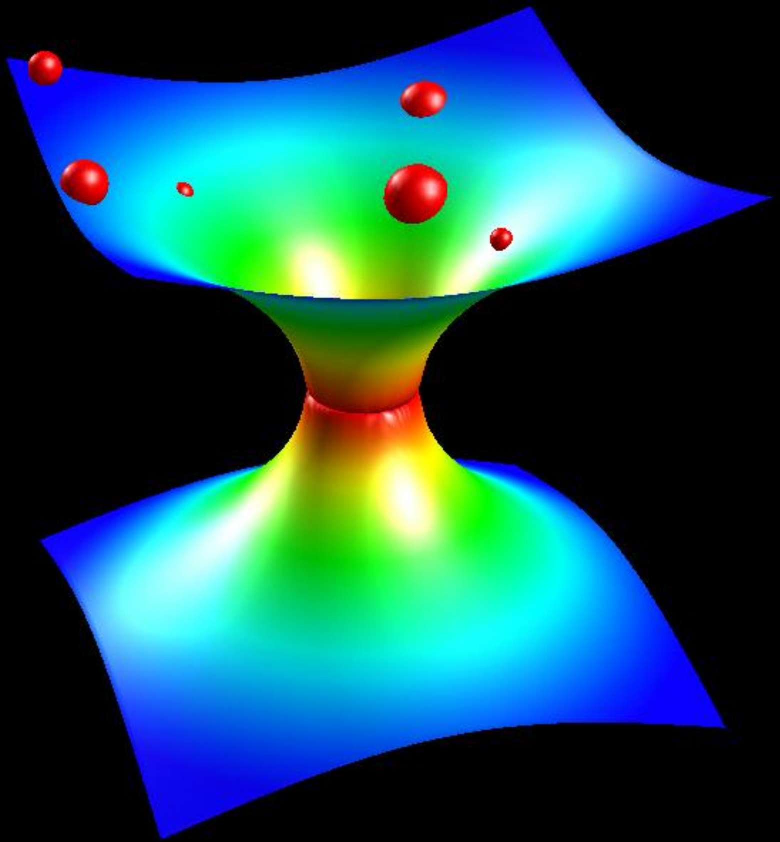


Figure from Thorne, *Black holes and time warps*.

Stephen Hawking - Wormholes

Mid-lecture Break (4 min. 41 sec.)

- Homework 5 is on WeBWorK; due this Saturday 4/16 at 8.30 am.



Embedding diagram of a stable wormhole, by Cliff Pickover. Bits of real matter (note their positive curvature in this embedding diagram!) are about to fall through. See http://sprott.physics.wisc.edu/pickover/.

The Star Trek DS9 wormhole

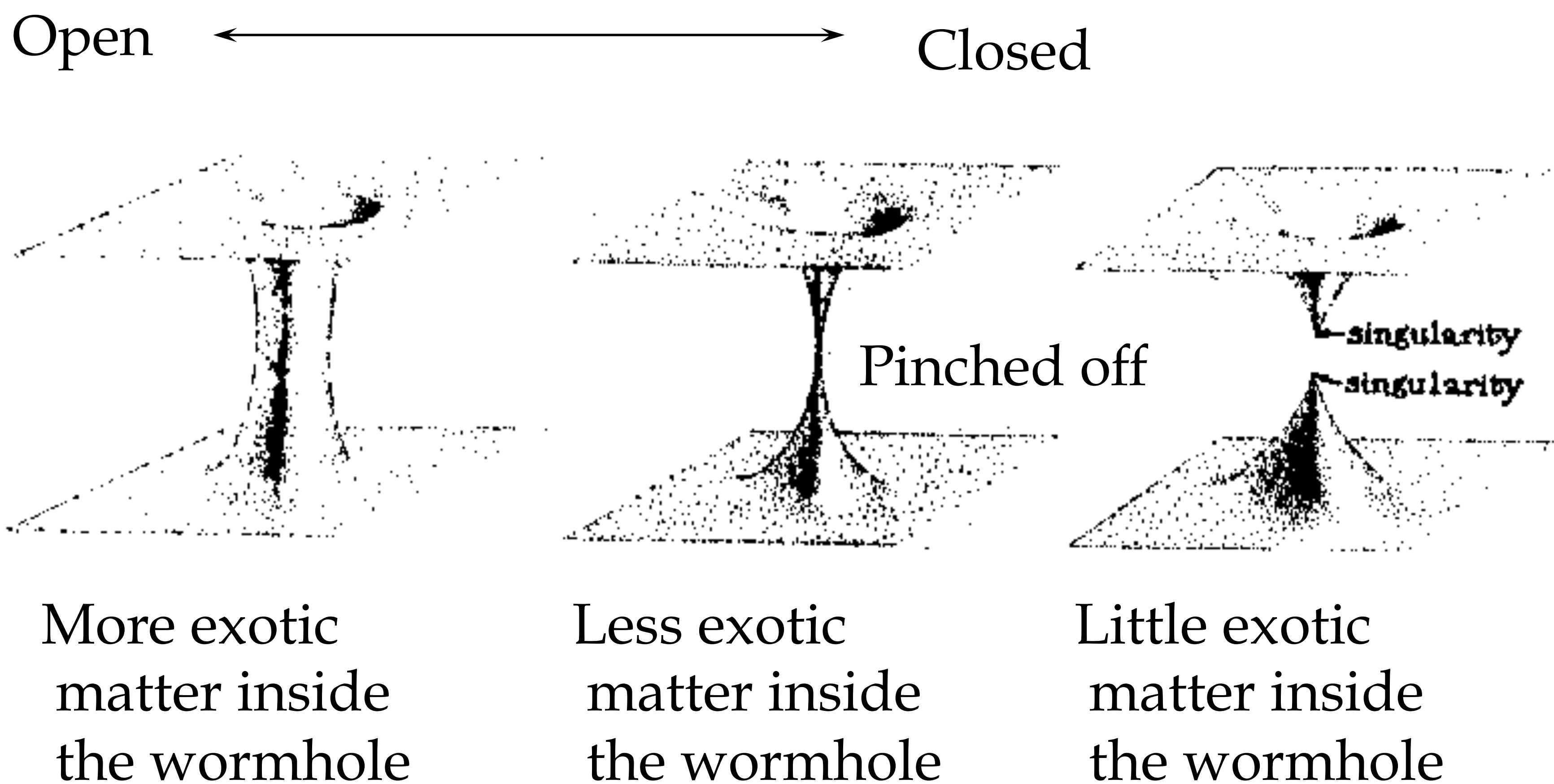
The most extensively-described fictional wormhole is surely the one in Star Trek: Deep Space Nine.

Wormhole maintenance: how the Star Trek DS9 wormhole might work

In *Star Trek: Deep Space Nine*, a stable wormhole provides a hyperspace shortcut from the "alpha" quadrant to the "gamma" quadrant of the Milky Way galaxy. In the story, it is inhabited by strange, Epicurean beings who permit travellers to pass through by opening and closing the wormhole.

- ***How do they open and close the wormhole?*** By rearranging large amounts exotic matter within the wormhole.
- ***Are the beings themselves made of exotic matter?*** They are intelligent. Something as orderly as intelligence can't arise from random vacuum fluctuations, so if the beings are themselves exotic, there must be other forms of exotic matter besides vacuum fluctuations in strong gravity.

Wormhole maintenance: how the Star Trek DS9 wormhole might work (continued)



Wormhole maintenance: how the Star Trek DS9 wormhole might work (continued)

- ***What does the wormhole look like from the inside, when it's closed?*** Like the neighborhood of a mass-density singularity: spacetime very strongly warped, time ceasing to exist at the center, *etc*. The non-existence of time at the center of the closed wormhole presumably gives the wormhole beings their peculiar view of time as something that can run forward, backward, stop, transpire out of sequence, and so forth.
- ***What does the wormhole look like from the inside when it's open?*** Like a spherically symmetrical space where everything is converging toward a center, gradually changing to a spherically-symmetric divergence from a center. It does not look like a tube in physical space, only in hyperspace.

Wormhole maintenance: how the Star Trek DS9 wormhole might work (continued)

- ***Is energy required to move through the wormhole?*** No; gravity accelerates you and pulls you through. It would take a great deal of thrust to hold still inside the wormhole, contrary to what's shown on the TV show.
- ***How does one open the wormhole from the outside?*** By sending a prearranged signal or beam of particles down the mouth; this arrives (highly accelerated or blueshifted) at the singularity, where the wormhole beings live, and when they detect it they proceed to rearrange the exotic matter.
- ***Does the wormhole have a horizon?*** Only when it's closed. (Then it has two, one at each mouth.)
- ***Is there a limit to how much matter can be moved through the wormhole at once?*** Yes; if there's much more normal matter than exotic matter inside, the wormhole will collapse.

Traversable, constructible wormholes

Advising Carl Sagan in the writing of *Contact* got Kip Thorne and his grad student Mike Morris interested in how an advanced civilization might build wormholes for transportation. They wrote a set of instructions based on the following principles:

- ❑ For simplicity, the wormhole's geometry is taken to be spherical and static.
- ❑ It must represent a solution to the Einstein field equations, of course, and one stable against small perturbations.
- ❑ It must have a throat that connects two regions of flat spacetime, so that it can be used to connect places in our Universe. Thus its equatorial-plane embedding diagram looks like the classic "hyperspace tunnel."

Traversable, constructible wormholes (continued)

- There should be no horizon.
- The tidal forces and accelerations experienced by a traveler must be bearably small; they took < 1 Earth g.
- A traveler must be able to cross the wormhole in a finite time in both the traveler's frame and in a frame of reference at rest with respect to the wormhole's mouths; they took < 1 year.
- The matter and fields that generate the wormhole's spacetime curvature must be physically reasonable.
- It should be possible to assemble the wormhole: that is, it should require energy much less than the mass of the Universe times c^2, and take time much less than the age of the Universe.

Traversable, constructible wormholes (continued)

The toughest constraints turn out to be on the material that generates the curvature:

- It must be able to withstand enormous tension: the pressure represented by this tension turns out to be approximately

$$P = \begin{pmatrix} \text{pressure at the center of the} \\ \text{most massive neutron stars} \end{pmatrix} \times \left(\frac{20\ \text{km}}{\begin{array}{l}\text{circumference} \\ \text{of throat}\end{array}} \right)^2$$

- This tension must exceed the material's mass density, and there is no such material known.

Traversable, constructible wormholes (continued)

- In fact, if it were to have this property and be part of the structure, it would appear in the viewpoint of a distant observer to have negative energy density: that is, it's **exotic matter**, again.
- So there doesn't seem to be any way to avoid exotic matter in the construction of a traversable wormhole. All they could do was consider ways to minimize the amount.

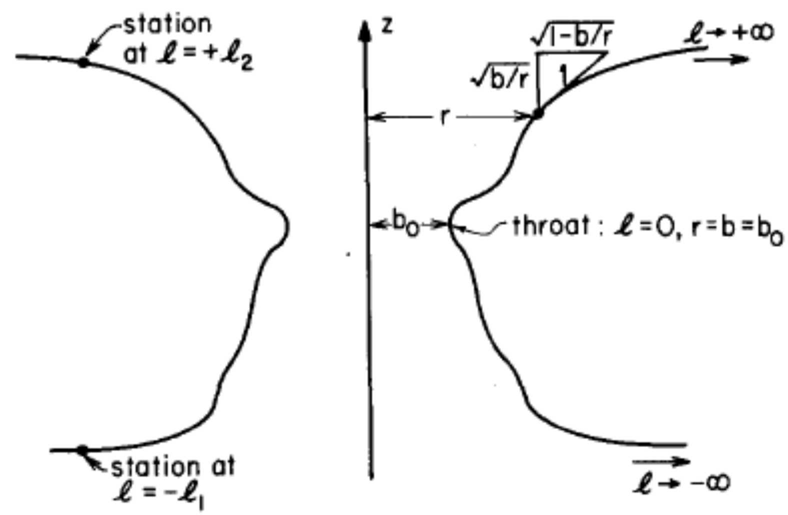


Fig. 2. Embedding diagram for a general wormhole, as seen in profile. (The diagram must be rotated about the vertical z axis to make it complete; cf. Fig. 1.).

Morris and Thorne 1987

Traversable, constructible wormholes (continued)

Properties of the minimum-exotic-matter solution:

- ❑ Exotic matter provided as a spherical shell slightly larger than the throat of the wormhole. All the other matter is non-exotic.
- ❑ Characteristic size of the mouths is rather large (600 times the size of the Solar system) in order to keep the accelerations modest.
- ❑ Acceleration no greater than one Earth g, small tidal forces, so traversing it would be perfectly comfortable.
- ❑ It would take 200 days to traverse the wormhole.
- ❑ How long it is in physical space determines the total mass.

So all we need is that exotic matter!

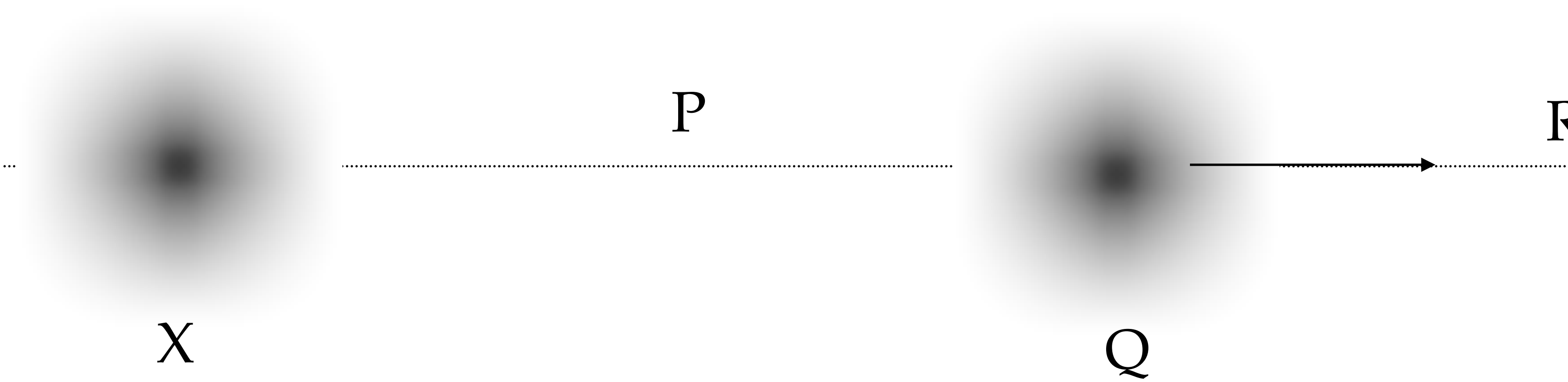
Wormholes as time machines

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.

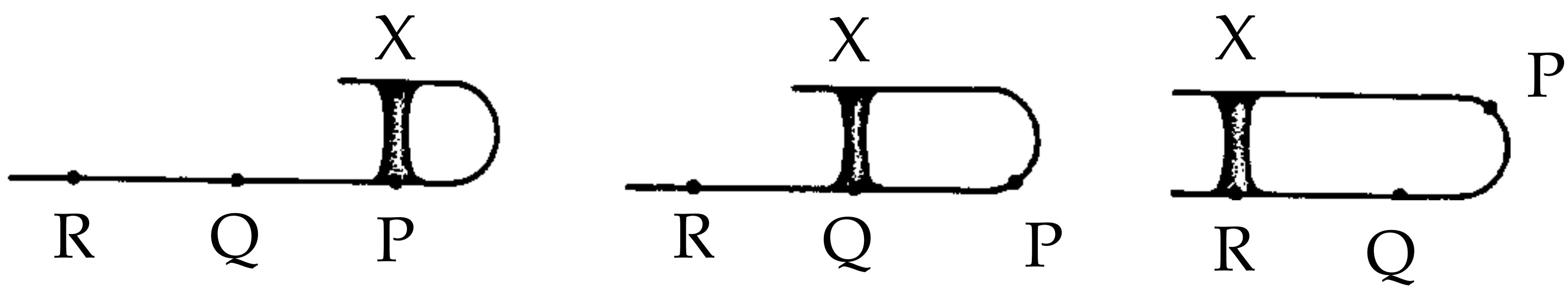
- Time dilation: clocks just outside the two mouths would appear to a distant observer to run at different speeds; the rates of time flow are different.
- From the inside, though, the mouths appear at rest with respect to each other; the rates of time flow are the same.
- This effect, the difference 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



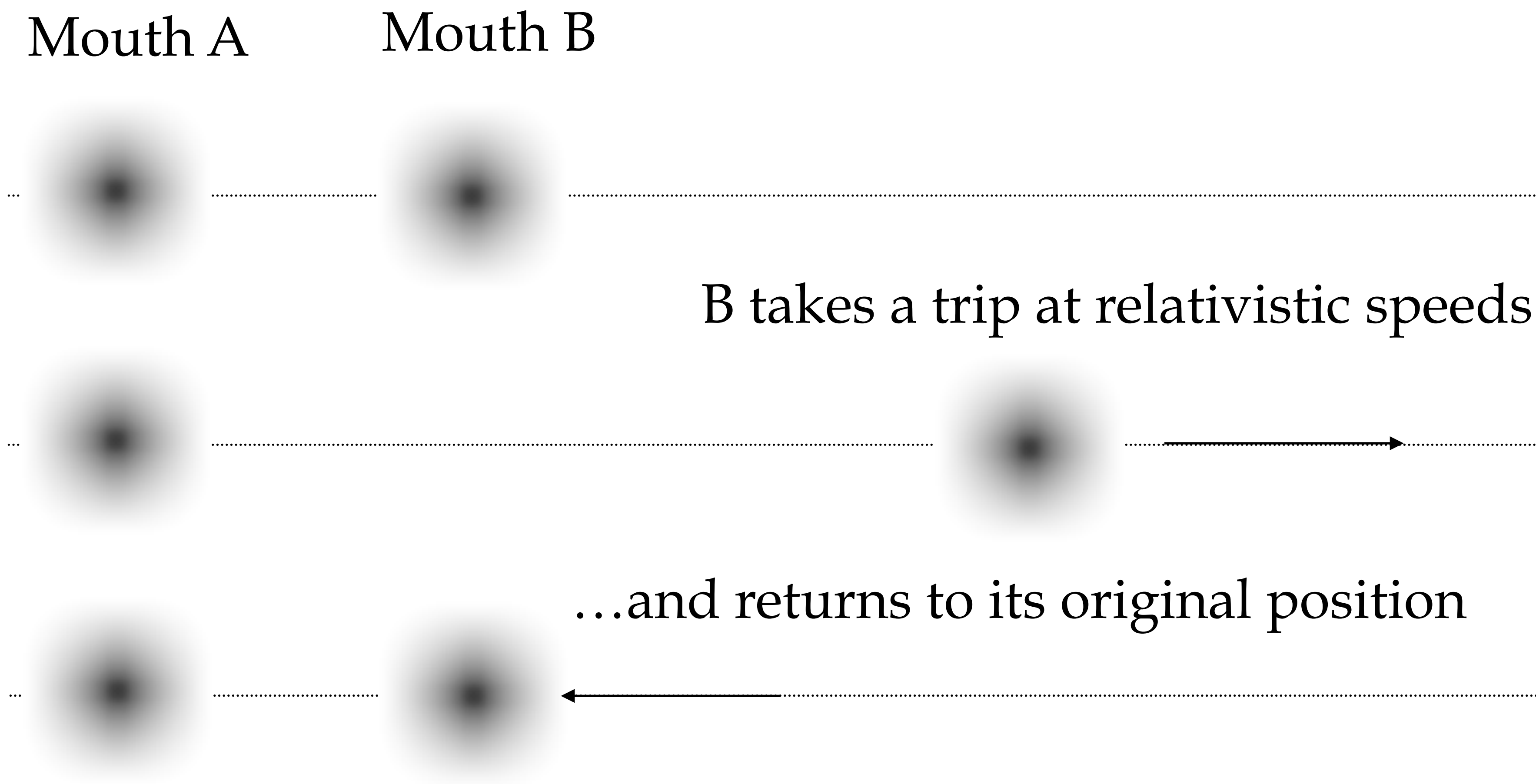
Hyperspace (at three instants of time)



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 opposite mouths and holding 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 "matricide paradox" come up! One could use a time machine, for example, for travelling back through time before one's birthday and killing one's mother.

Does physics prevent one from being born and travelling back through time in the first place?

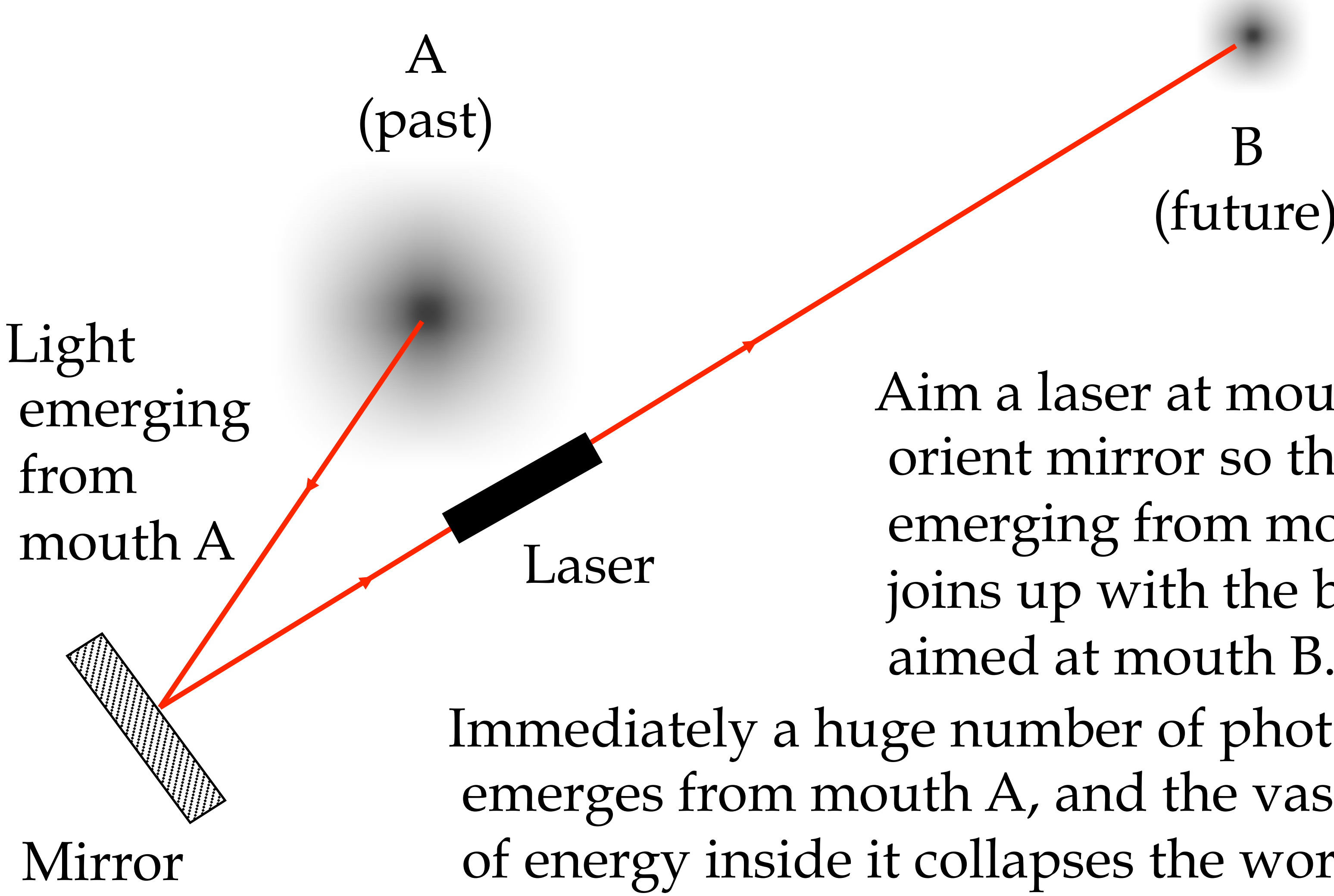
- **Maybe**. How is it that one can start with laws of physics like the Einstein field equation, that have cause and effect built in, and derive from them violations of cause and effect?
- **Maybe not**. What about quantum mechanics? Vacuum fluctuations, for instance, have no "cause." If quantum behavior (associated with mass-density singularities) is inherent in the wormhole, one could still exist after committing paradoxical matricide.

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.

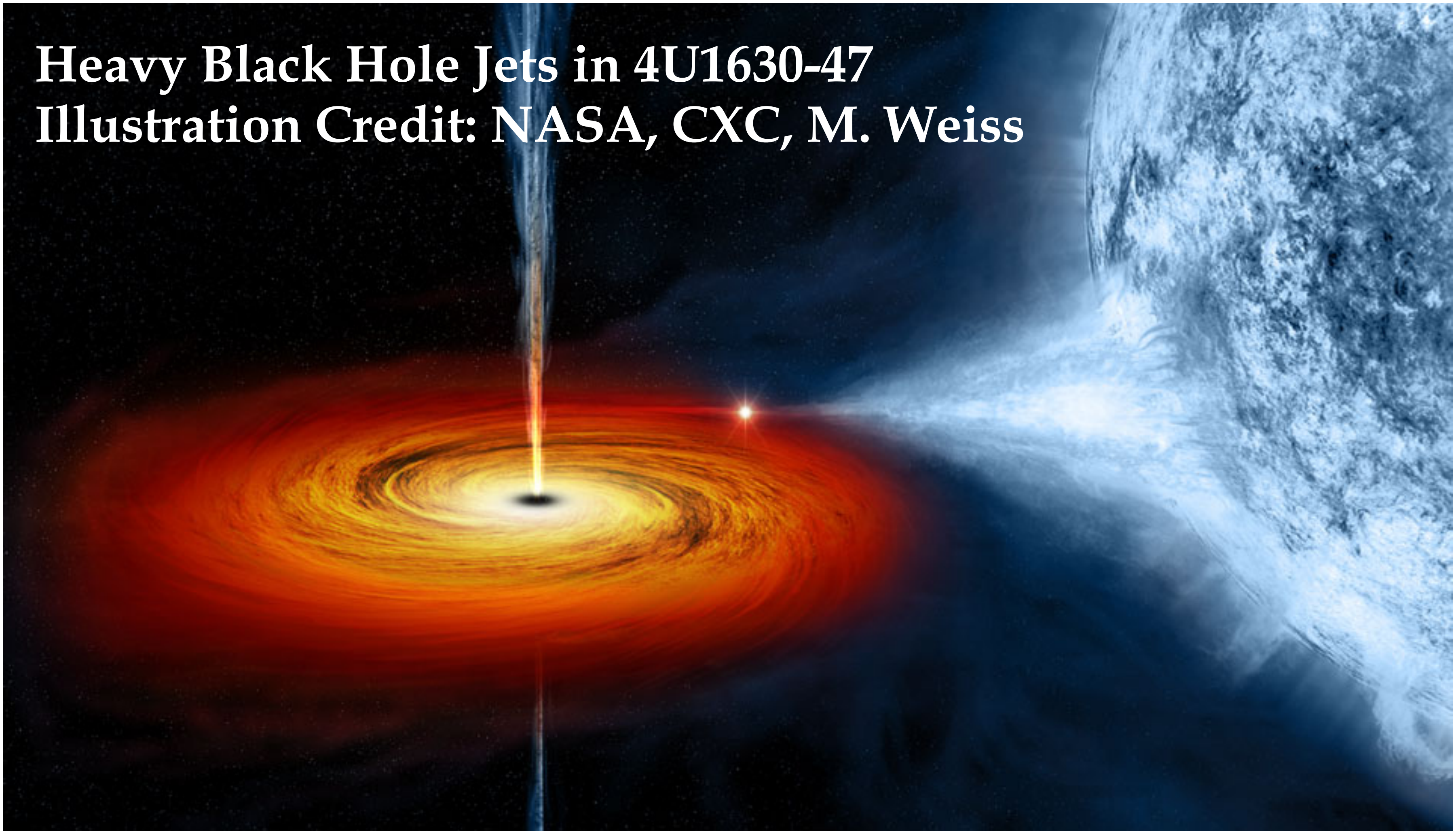
Immediately a huge number of photons emerges from mouth A, and the vast increase of energy inside it collapses the wormhole.

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

  That would render all wormhole time machines unstable.
- 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.

Done!


Heavy Black Hole Jets in 4U1630-47
Illustration Credit: NASA, CXC, M. Weiss