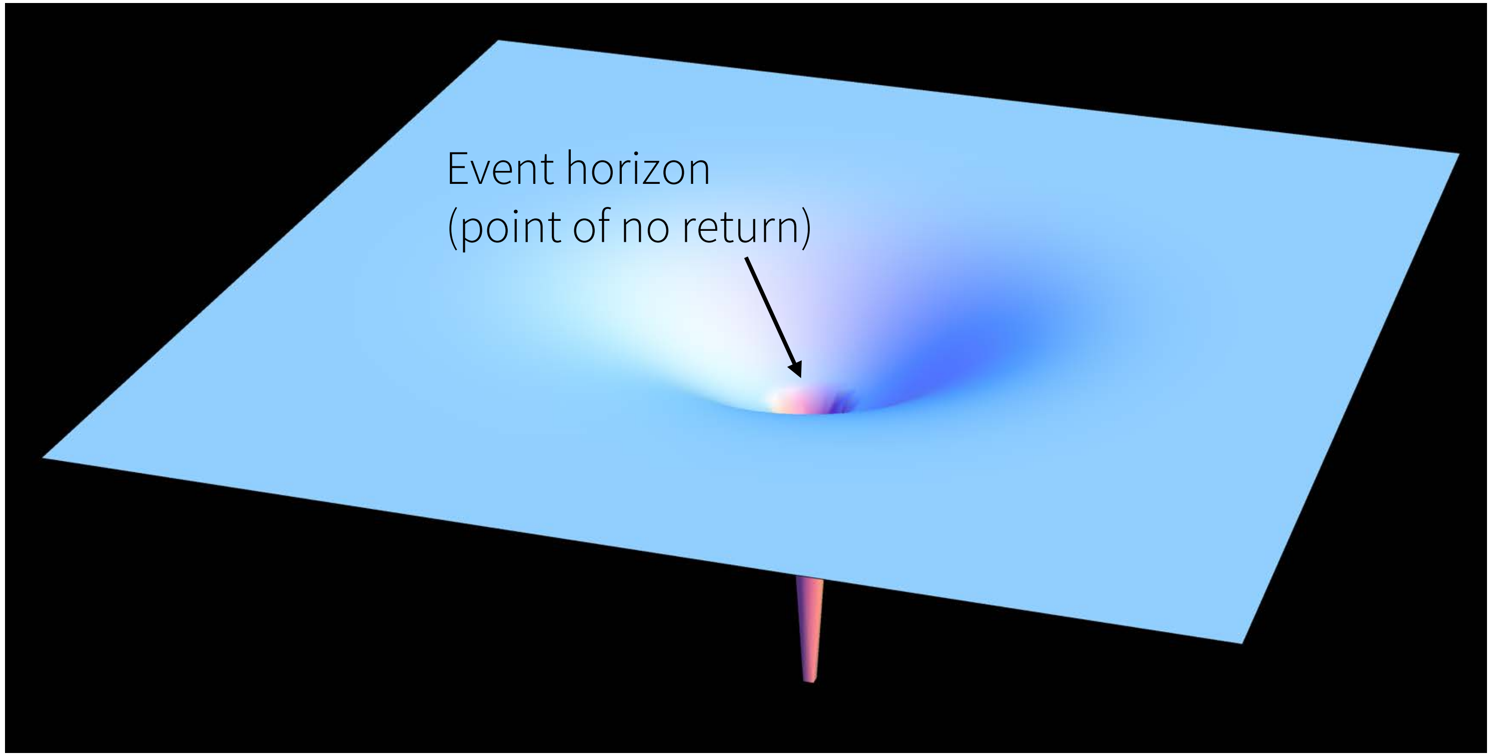
20: In a Nutshell (Part 2)

Physics 17: Black Holes and Extreme Astrophysics

L14.9

Black Holes in General Relativity



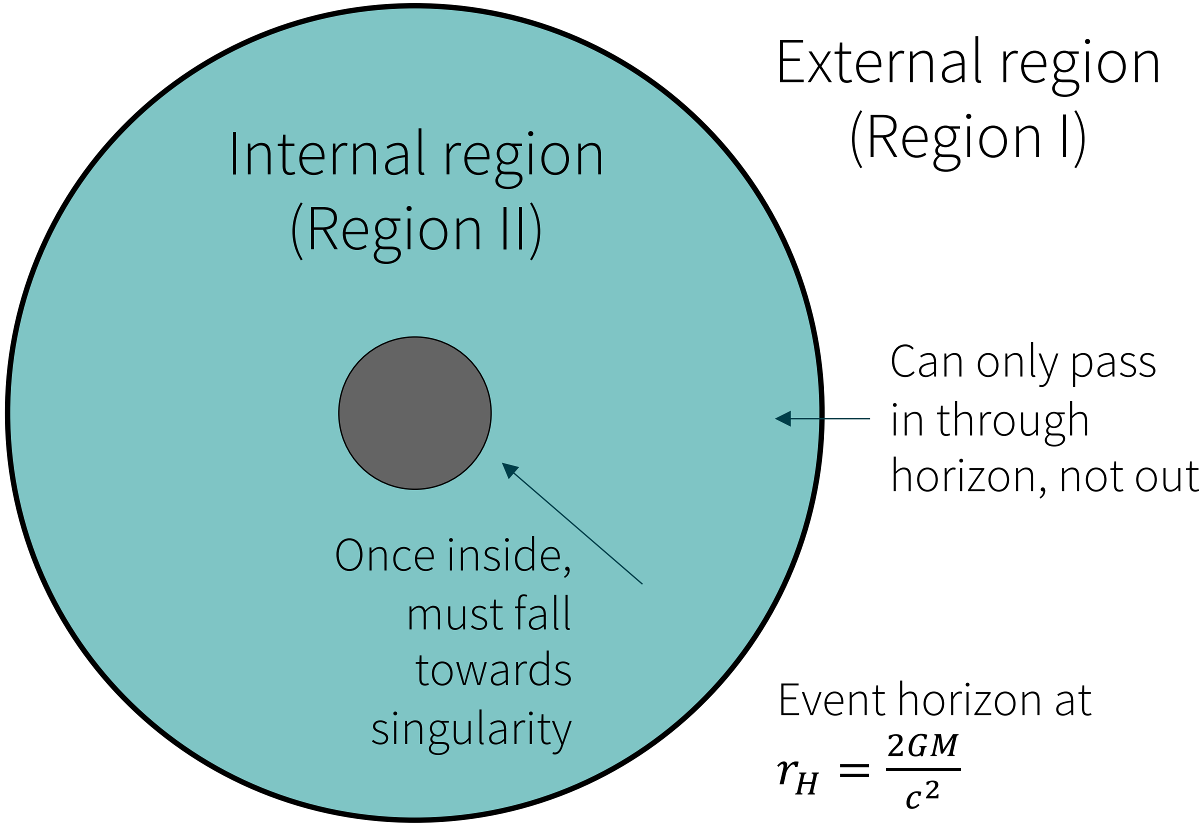
The Schwarzschild spacetime is the solution of Einstein's equations of general relativity around a compact point mass, and describes a black hole

"Matter tells space how to curve. Space tells matter how to move" – John Archibald Wheeler

- Compact objects produce extreme spacetime curvature
- At large distances, the curvature is slight and the gravitational force is consistent with Newtonian gravity
- At the event horizon, curvature is strong
- All geodesics within the event horizon go towards the singularity — once inside the event horizon, the only way is inwards! WILtY

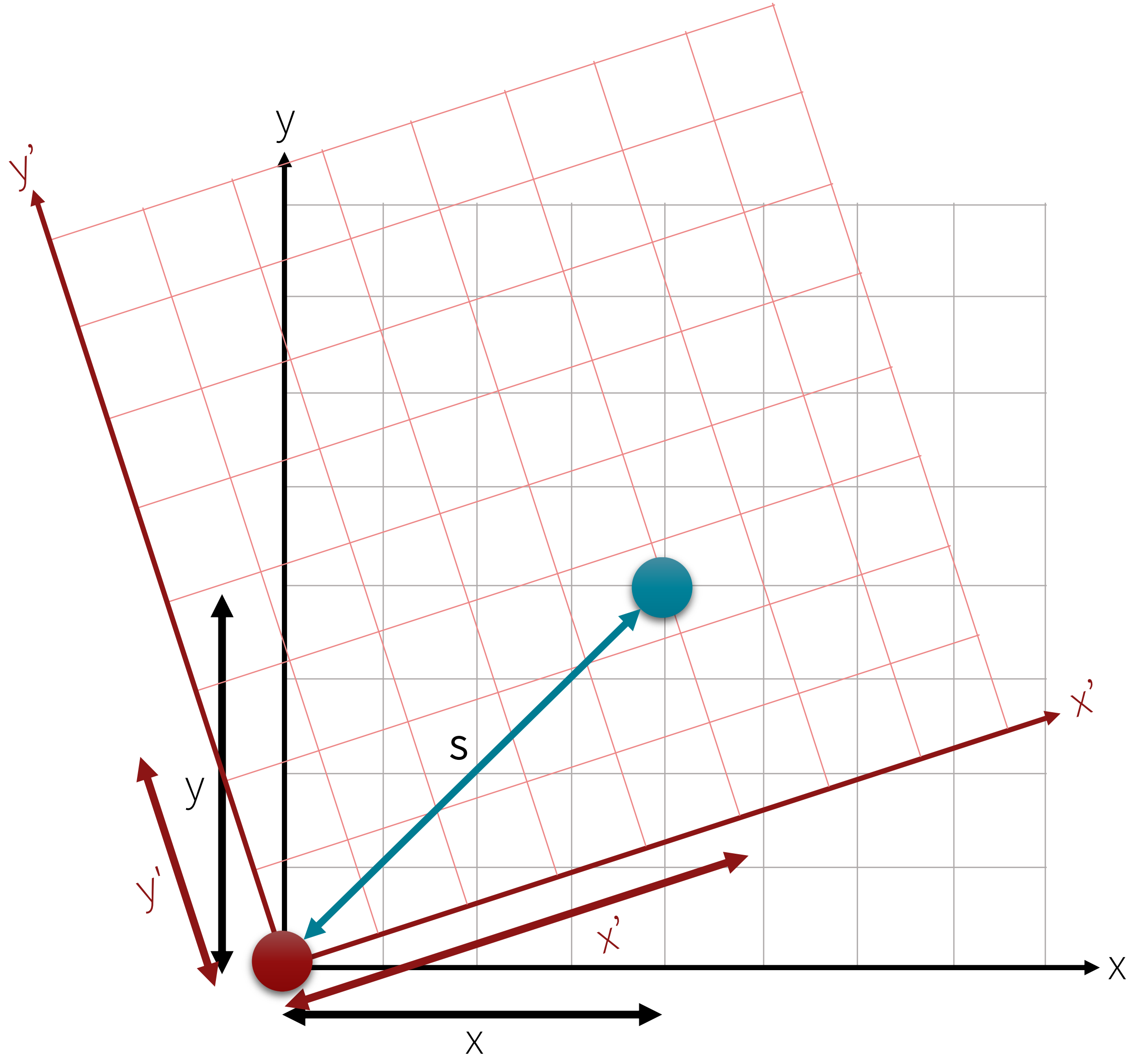
L6.13

Schwarzschild Spacetime



- In the "exterior region" time is timelike (we must travel forward in time), and radius is spacelike (we can travel around in space)
- Can only pass one way through the event horizon (can fall in, but cannot leave)
- Inside the event horizon, time becomes spacelike and radius becomes timelike (inside the horizon, radius advances, you must travel towards the singularity, which is in your future)

Space and Time



Point P is a distance s from the origin (O)

Can measure its co-ordinates (x, y) on a grid

$$s^2 = x^2 + y^2$$

Can draw another, rotated grid and measure its co-ordinates (x', y')

$$s^2 = x'^2 + y'^2$$

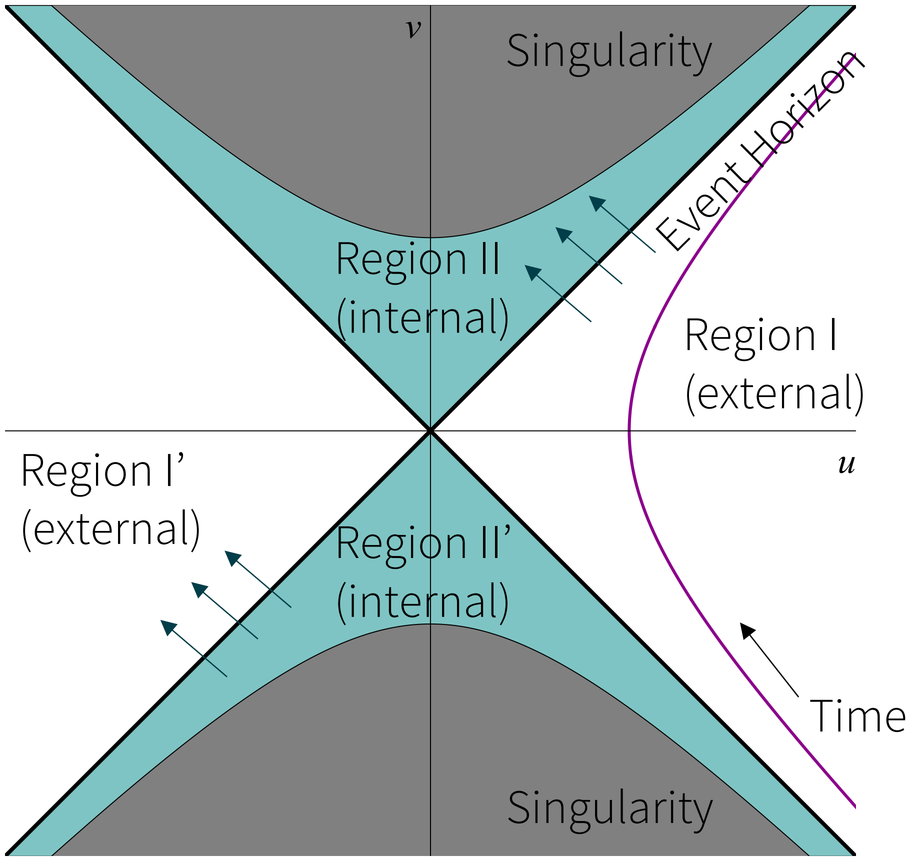
In this case, the new co-ordinates x' and y' are each a mixture of x and y

It doesn't matter what co-ordinate system you use, the displacement between the two points must always be s

$$x^2 + y^2 = x'^2 + y'^2$$

TMI

The Extended Schwarzschild Spacetime



We are only considering the radial co-ordinate. Each point represents a sphere (can be at any position around the center at each radius)

Instead of mapping spacetime in time and radius, we can create a map in new co-ordinates, u and v, that are mixtures of radius and time

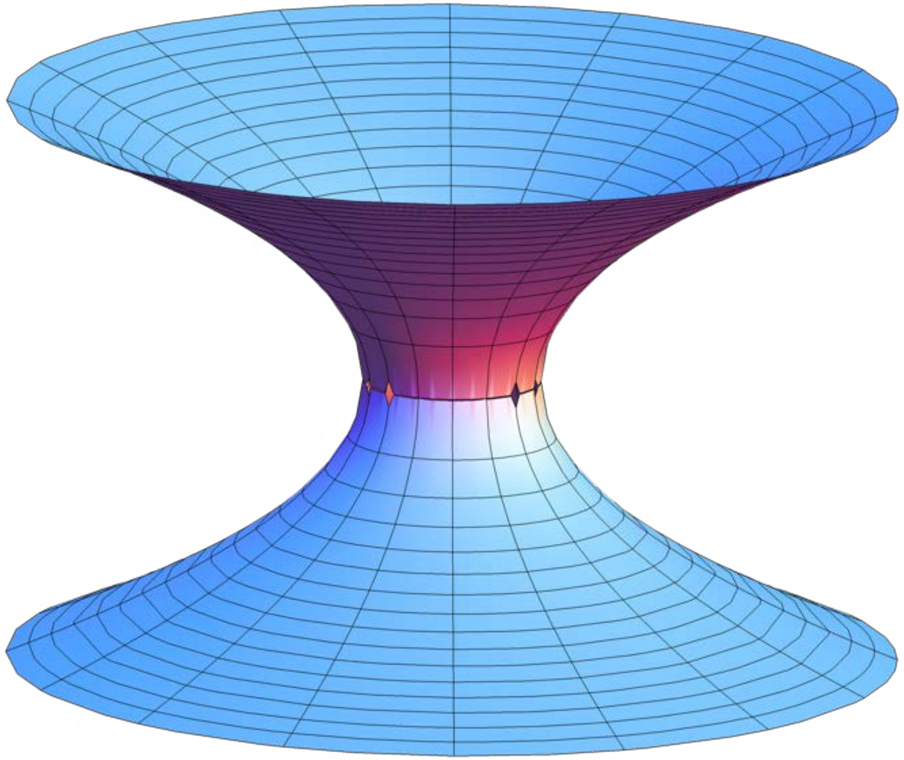
The conventional solution to the Schwarzschild spacetime describes a black hole

- Can only travel from the external region (I) to the internal region (II), not the other way (you can't leave the event horizon!)

The space and time co-ordinates we are used to cover only half of the space described by our new u and v co-ordinates. There are 2 more regions:

- The other "external region" (I') is the same as I and represents another Universe
- But, in this case, can only travel from the internal region (II') from the external region (I') — you can only leave the horizon
- The singularity is in your past
- This part of the Schwarzschild solution to Einstein's equation represents a white hole

The Einstein-Rosen Bridge (a Wormhole)



The wormhole is a circle in a 2D space, so would be a sphere in 3D space

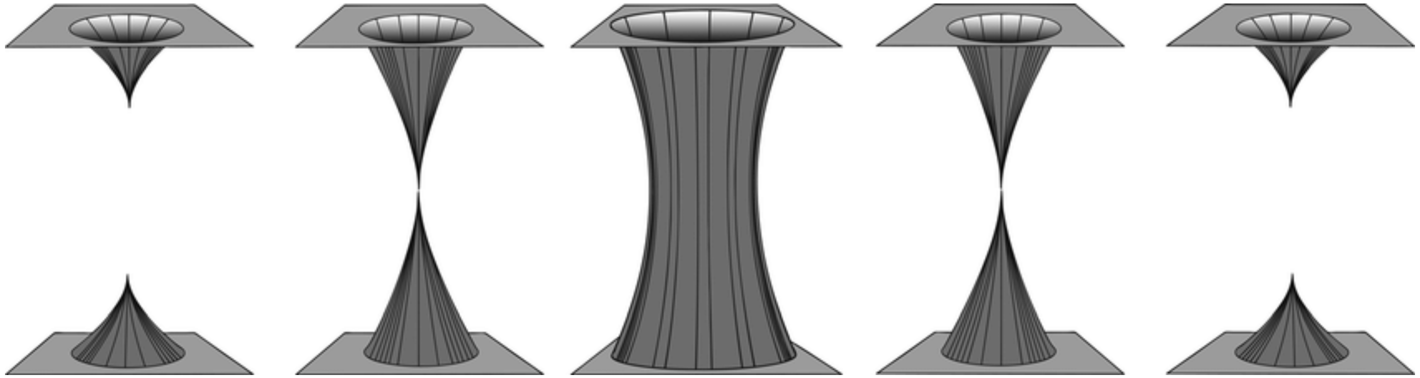
Region I and region I' (the other universe) are connected at $u = v = 0$

The horizons in each universe are connected!

A **wormhole**

Can connect two different Universes, or distant parts of the same Universe!

Wormholes don't last long!



- Begin with 2 disconnected universes, each with a singularity
- Singularities join and form non-singular bridge
- Wormhole contracts and then pinches off

Inside the event horizon, spacetime is dynamic — radial co-ordinate, r, is timelike and keeps advancing

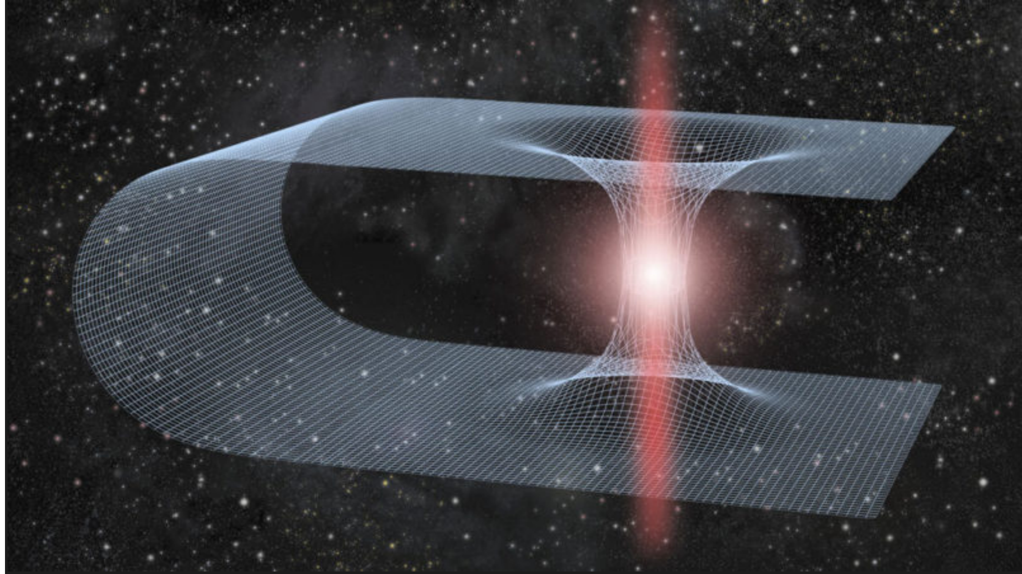
The wormhole only exists at $u = v = 0$ (u and v are mixtures or r and t)

A photon, travelling at the speed of light, would reach the center of the wormhole right as it pinches off, and would get trapped

Massive objects must travel slower than the speed of light, so would not make it through the wormhole before it pinches off

Could we keep a wormhole open?

- To keep a wormhole open, would need to counteract the curvature of space around the singularity (that gives rise to the force of gravity)
- The curvature and gravity are due to the total matter and energy content of the Universe
- Need something to produce negative curvature (i.e. with negative energy) to hold the wormhole open long enough to travel through!
- Could dark energy keep a wormhole open? (which accelerates the expansion of the Universe)

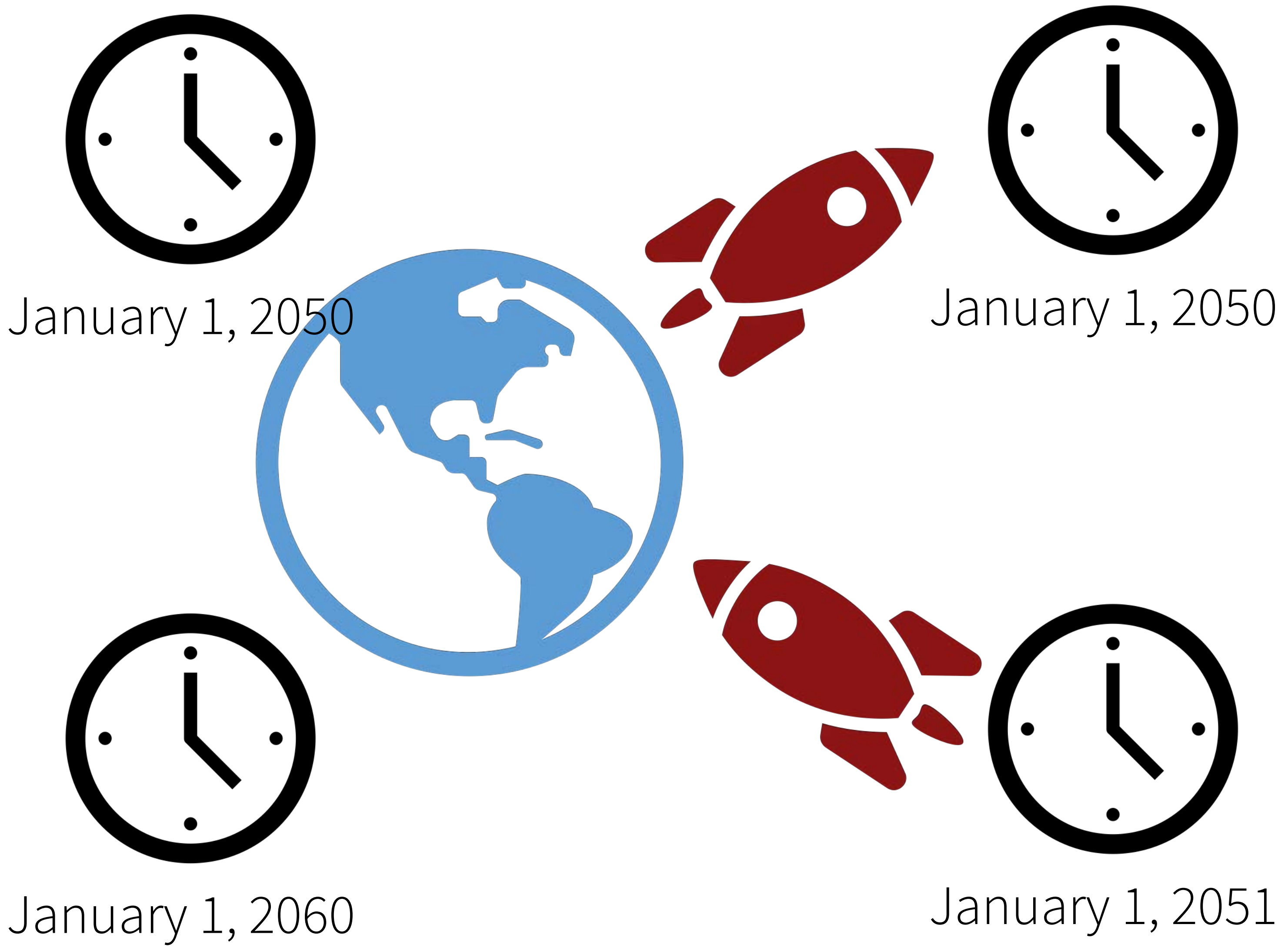


Quantum mechanics to the rescue?

- Empty space is not empty – always fluctuating – has zero energy on average
- Curvature of space through wormhole distorts quantum fluctuations and can give them slight negative energy on average (like the Casimir effect)
- Could slow down collapse long enough to let a photon travel through
- BUT as soon as anything passes through, it has positive energy. When the total energy in the wormhole is positive, it collapses!

HW2

The Twin Paradox



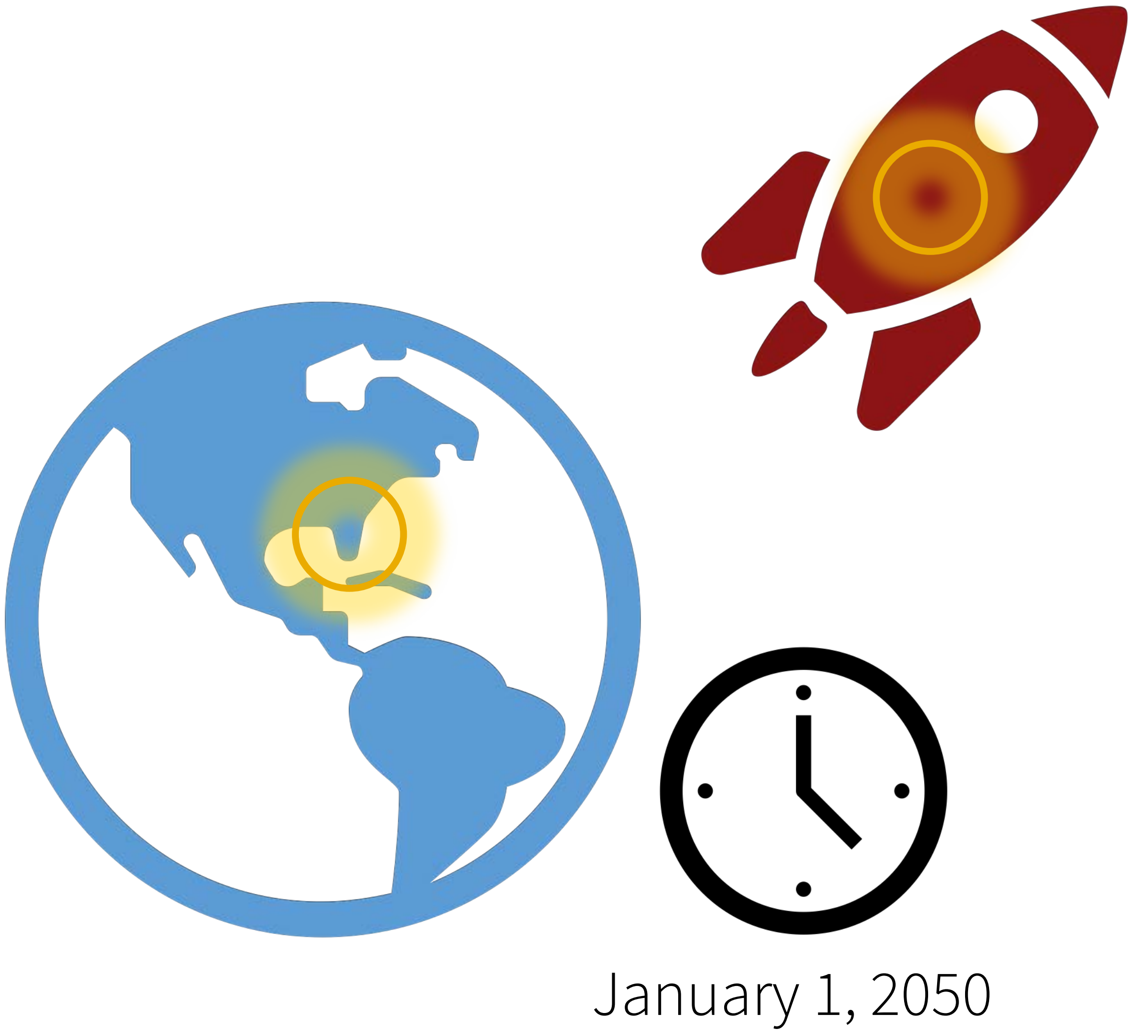
Alice & Bob are two twins

Alice sets out on a 10 year spaceflight, travelling at a significant fraction of the speed of light (0.995c), Bob stays behind

Special relativity (time dilation) tells us that Alice's clock is ticking more slowly than Bob's while she is moving

When Alice returns, less time has elapsed for her (1 year), so she is younger than Bob

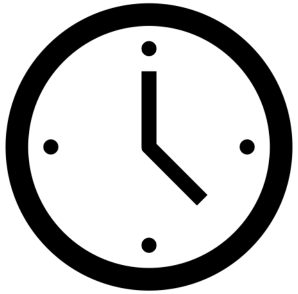
Turning a wormhole into a time machine!



We create a wormhole, put one side on a spaceship, and take it on a flight for 10 years, travelling close to the speed of light (0.995c) and bring it back to Earth. We leave the other side of the wormhole at mission control

When the spaceship returns, 10 years has passed on Earth, but much less time has passed on board (1 year)

Time through the Wormhole



January 2, 2050

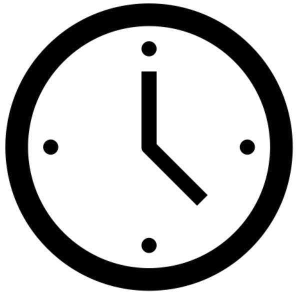
Clock at
mission control

Clock on spaceship seen
through wormhole

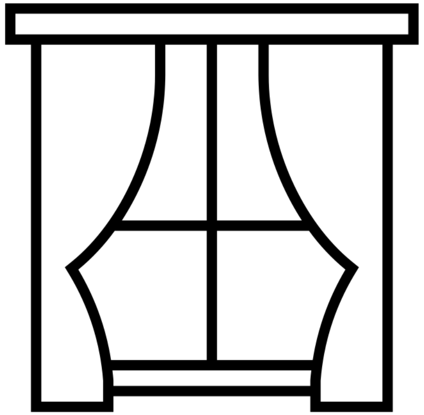
Time is synchronized through the wormhole

Clocks on each side of the wormhole appear to tick at the same rate when observed through the wormhole

When does the rocket return?



January 1, 2051



Out the window,
no rocket

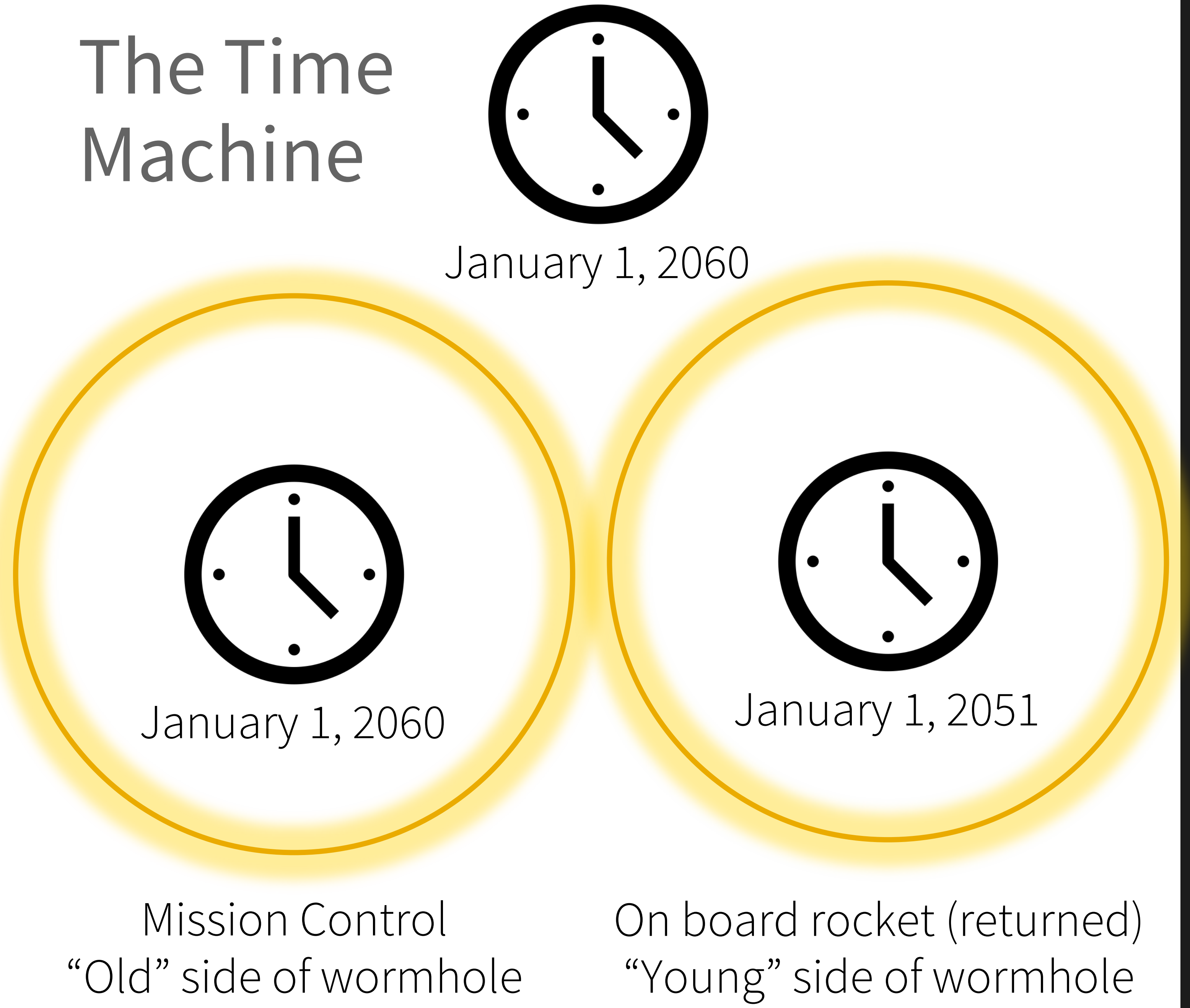
Through wormhole, we see
rocket is back on Earth

From the point of view of the spaceship, the journey only lasts 1 year. 1 year later, the spaceship is back on Earth

From mission control, if we look through the wormhole, we will see the spaceship back on Earth

But if we look out of the window, the spaceship is not there! We can still see it flying through our telescopes!

The Time Machine



When the rocket returns to Earth with the other side of the wormhole, time is hooked up differently though the wormhole and outside

Only 1 year has passed on the rocket, but 10 years on Earth

Looking through the “young” side of the wormhole on the rocket, only 1 year has passed, so through wormhole is mission control as it was 9 years ago!

What’s the catch?

- We need to keep the wormhole open! (Slide 7)
- Quantum of gravitational instabilities could destroy the wormhole if the two ends are brought close together when their times are out of sync
  - Light going round from one mouth of the wormhole to the other repeatedly can be amplified and cause instabilities
- The laws of physics might preclude time travel, though this is not proven
- Chronology protection conjecture — timelines should be protected from meddling physicists!
  - Don’t want to create any paradoxes (e.g. preventing yourself being born, going back in time and destroying your own time machine, etc.)

<u>If</u> a wormhole can exist and stay open, time travel is a natural prediction of General Relativity

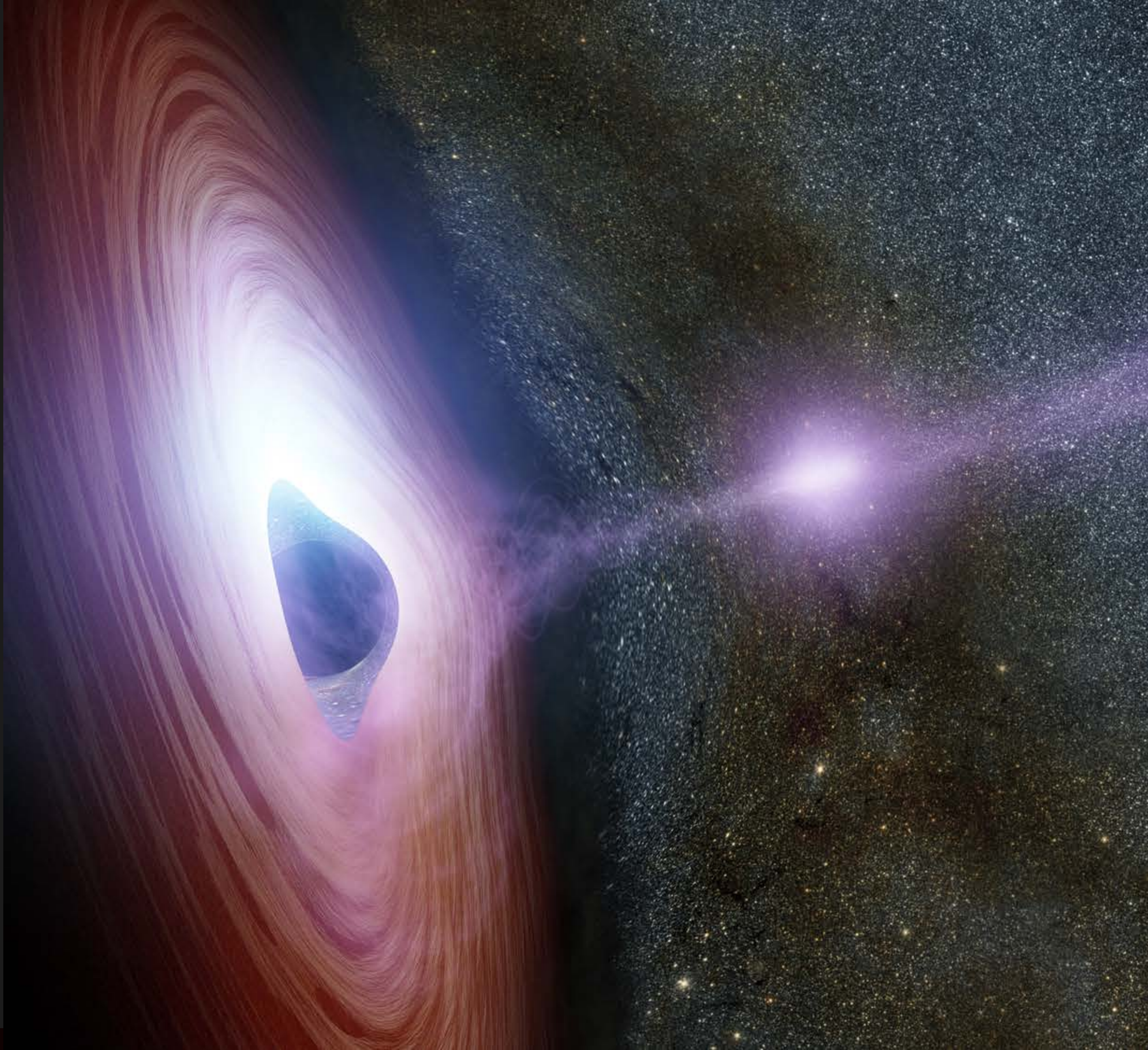
However, can only travel back to the moment in time the wormhole was turned into a time machine, not before


The frontiers of black
hole research…

L7

Exactly how is energy released as gas falls into a black hole?

- We know that the gravitational energy lost as gas falls into black holes through the accretion disk, energy is released that powers bright light sources and jets
- But how exactly does the energy get fed into the corona?
- How does the jet get launched?
- How much of the energy comes from the spin of the black hole?



L8

How does a black hole govern the growth of galaxies?

- The energy output as matter falls into a supermassive black hole in the center of a galaxy is enough to limit the growth of the galaxy, and to stop the formation of new stars
- Black holes must have played an important role in the formation of structure in the Universe
- But how does the energy get transferred from the accretion disk and jet into the galaxy?
- What controls this process and why does the black hole switch off leaving a galaxy like our own?

L8

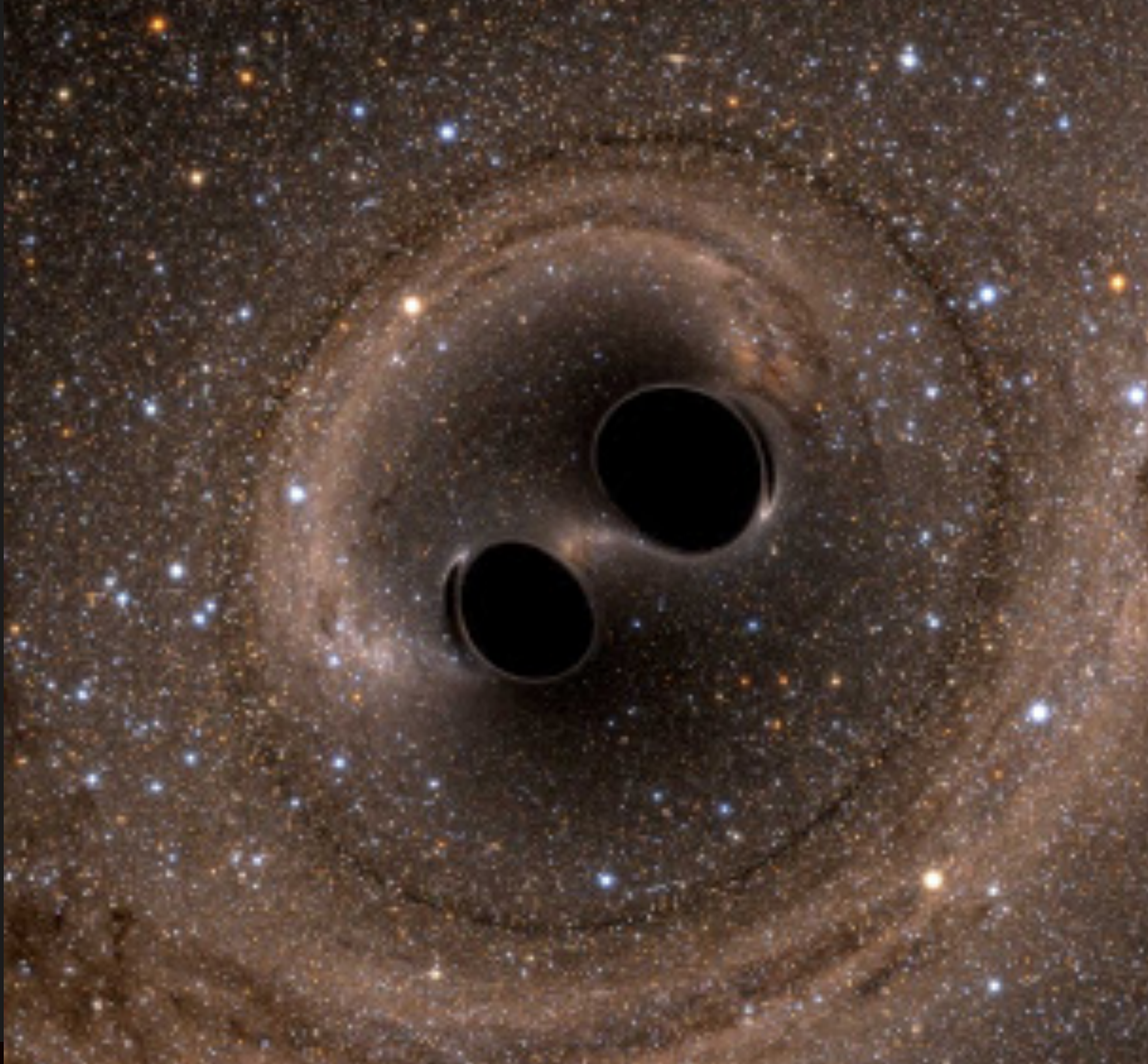
How did the supermassive black holes get in the centers of galaxies?

- Early population of massive stars that became black holes at the ends of their lives and merged?
- Direct collapse of a large cloud of gas to a black hole in center of a gravity?
- Distant quasars (observe din early Universe) already have big black holes — supermassive black holes must have grown faster than we thought they could!
- When did the first black holes form?

L19

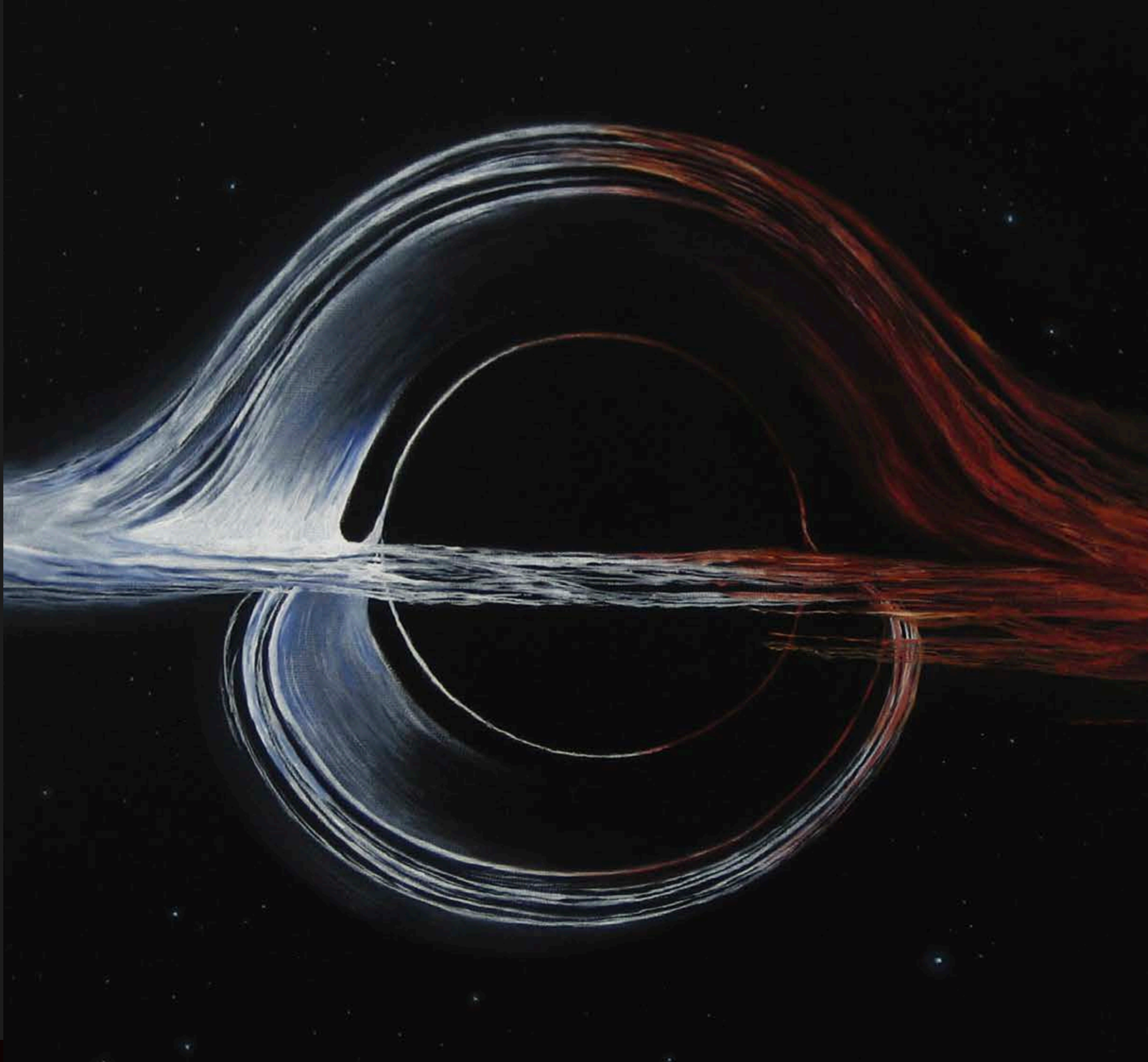
Why are the black holes that LIGO saw merge so big?

- We see stellar mass black holes in X-ray binaries with masses $\sim 10 M_{\odot}$
- Supermassive black holes in the centers of galaxies are $10^6 \sim 10^9 M_{\odot}$
- Why are the binary black holes that merge $50 \sim 100 M_{\odot}$?
- How do you make a black hole that size? A massive star that fails to explode as a supernova?

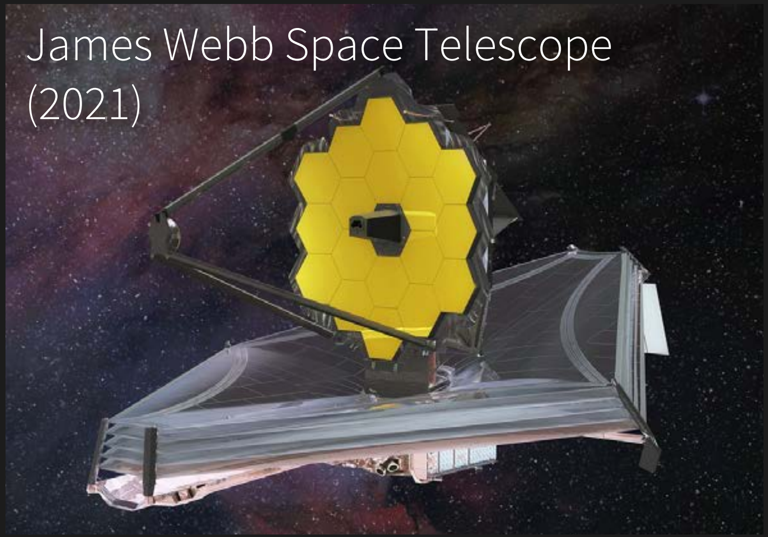


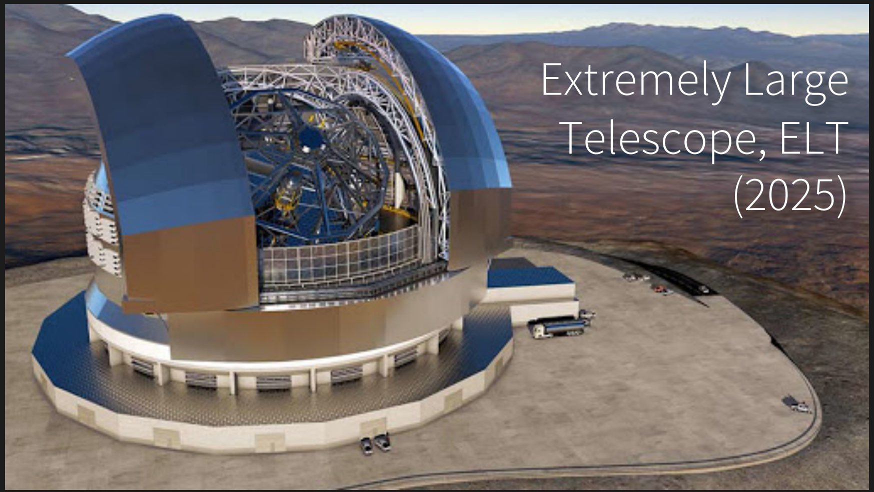
Was Einstein right?

- General relativity as a theory of gravity is extremely well tested in our Solar system (weak gravity)
- Gravitational waves observed when black holes merge agree very well with general relativity (strong gravity, on small scales close to the event horizon)
- But are black holes completely described by general relativity?
- How does quantum mechanics fit in?



And new telescopes coming to help answer these questions…





BigI

- Start with Newton's laws of motion and gravity, add Einstein's theory of relativity to understand and explore black holes
- Black holes are all over the Universe! Stellar mass black holes when massive stars die, supermassive black holes in the centers of galaxies
- Black holes power some of the most extreme phenomena we see in the Universe (bright X-ray sources, quasars, jets)
- We can observe black holes in many different ways and have even captured an image of a black hole's shadow!
- Black holes played an important role in the formation of galaxies and structure in the Universe
- Warped space, ripples in space (gravitational waves) from cosmic collisions, singularities, wormholes and time machines!