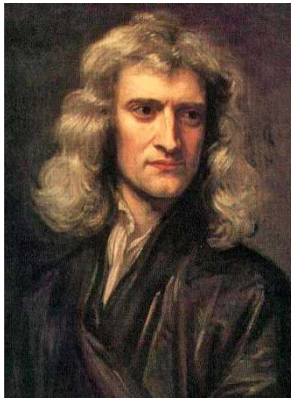
Models of Gravity

Why does this rod bend?

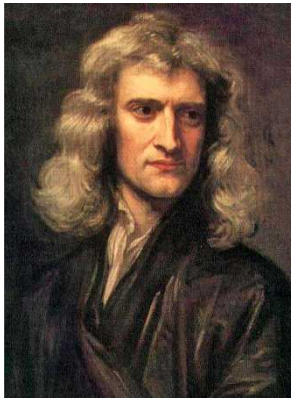
"That one body may act upon another, at a distance through vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking, can ever fall into it."

—Isaac Newton

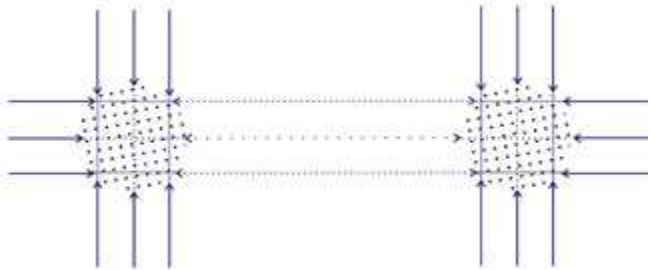


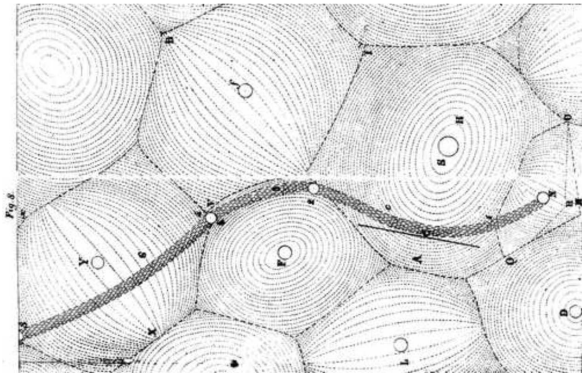
"I have not yet been able to discover the **cause** of these properties of gravity from phenomena and I feign no hypotheses.... It is enough that gravity does really exist and acts according to the laws I have explained, and that it abundantly serves to account for all the motions of celestial bodies."

—Isaac Newton



Scientists attempted to find **physical explanations** for a gravitational force…





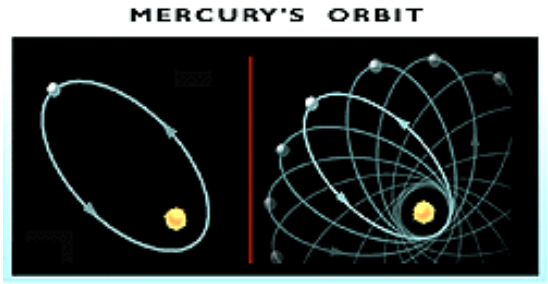
Nicolas Fatio de Duillier (1690): Space is filled with randomly moving particles or waves, pushing on bodies from all directions. Nearby bodies shield/shadow one another, resulting in net forces that look like attraction.

Descartes (1644): Believed empty space cannot exist, so must be filled with aether, which moves in circular motion (vortices) around bodies. These vortices exert forces on each other, and other bodies, and that's gravity!

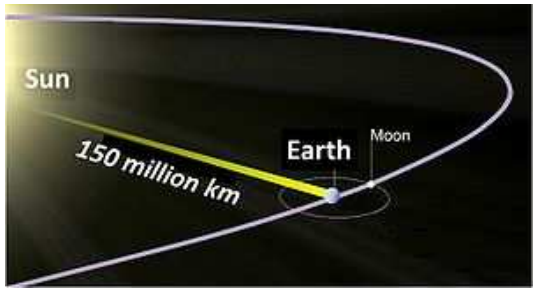
Etc…

…but they all **FAILED**.

Later, there were **more serious problems;** the force model was discovered to not work:



Experiment: Force model predicts wrong orbits

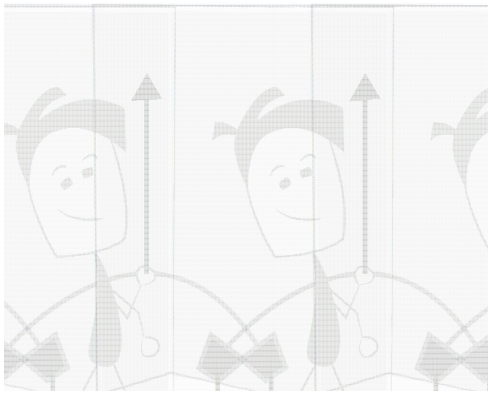


Theory: Force model violates speed of light limit

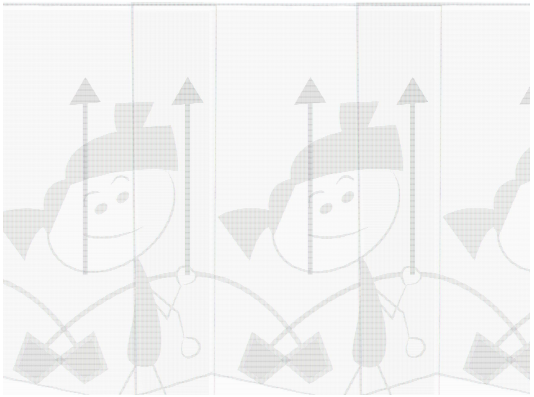
By the early 1900s many scientists, including Einstein, recognized that the **force model of gravity was in serious trouble**, and were looking for a **new, better model**.

But where to even begin the search?

Einstein considered an **acceleration model**:



Force Model



Acceleration Model

Also explains the bending rod, *but without having to invent a "mysterious invisible" force*!

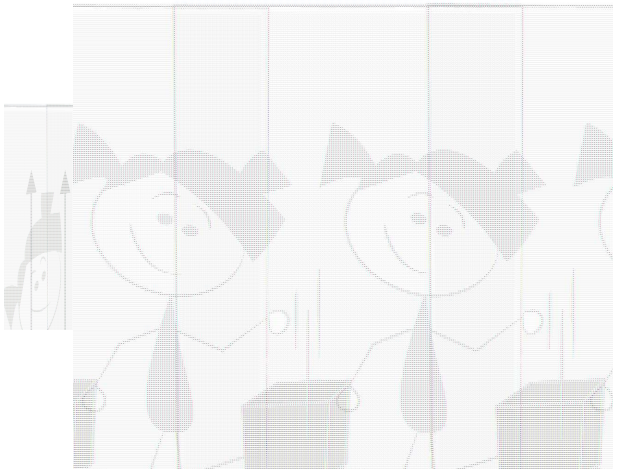
How does the acceleration model explain **WEIGHT**?

Alice must exert a force **up** on the box to make it **accelerate up**, to match the upward acceleration of herself and the room.

More massive boxes require a **greater upward force**.

These are **exactly** the features of weight.

How does the acceleration model explain **FREE-FALL**?



When Alice releases the box (stops pushing up on it), the box **stops accelerating** up. It continues to move at a **constant** speed, the speed it had just as she released it.

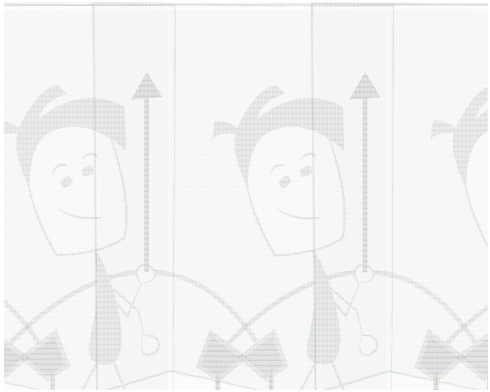
But she and the room **continue** to accelerate up (move faster and faster). The floor accelerates **up** toward the box and hits it. **To Alice**, it *appears* that the box accelerates **down** and hits the floor.

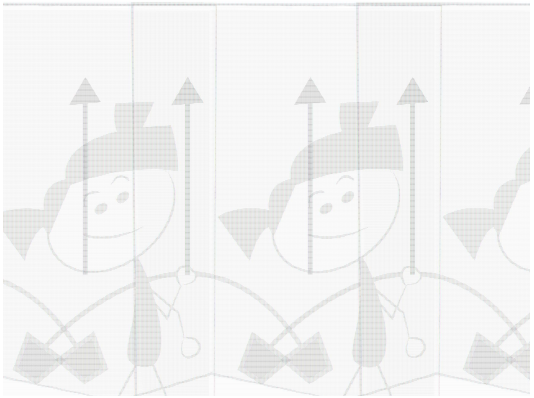
The “downward acceleration” is independent of mass of box (**explaining Galileo’s famous experiment**).

Acceleration Model of Gravity

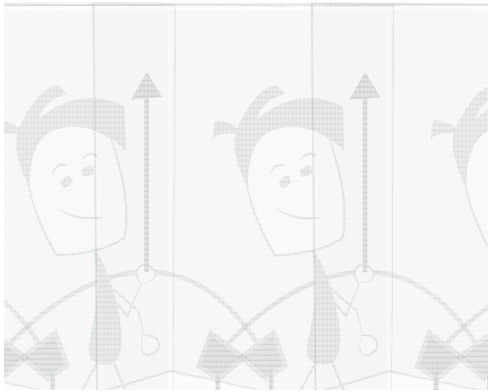
So, we have **two** models, that **both explain simple gravity on Earth, equally well**:

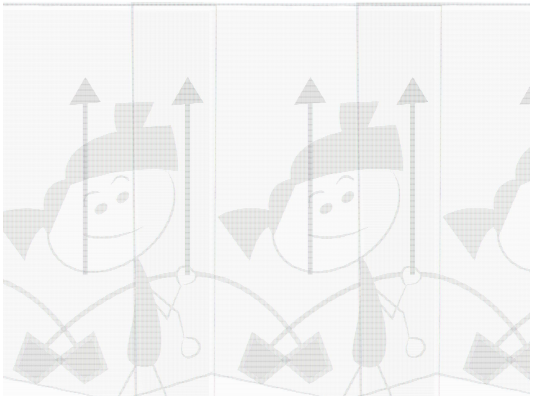
- **Force model:** The Earth exerts a force on objects, pulling them down towards the ground.
- **Acceleration model:** There is no force pulling down; the ground is accelerating up!





What's wrong with this proposal?



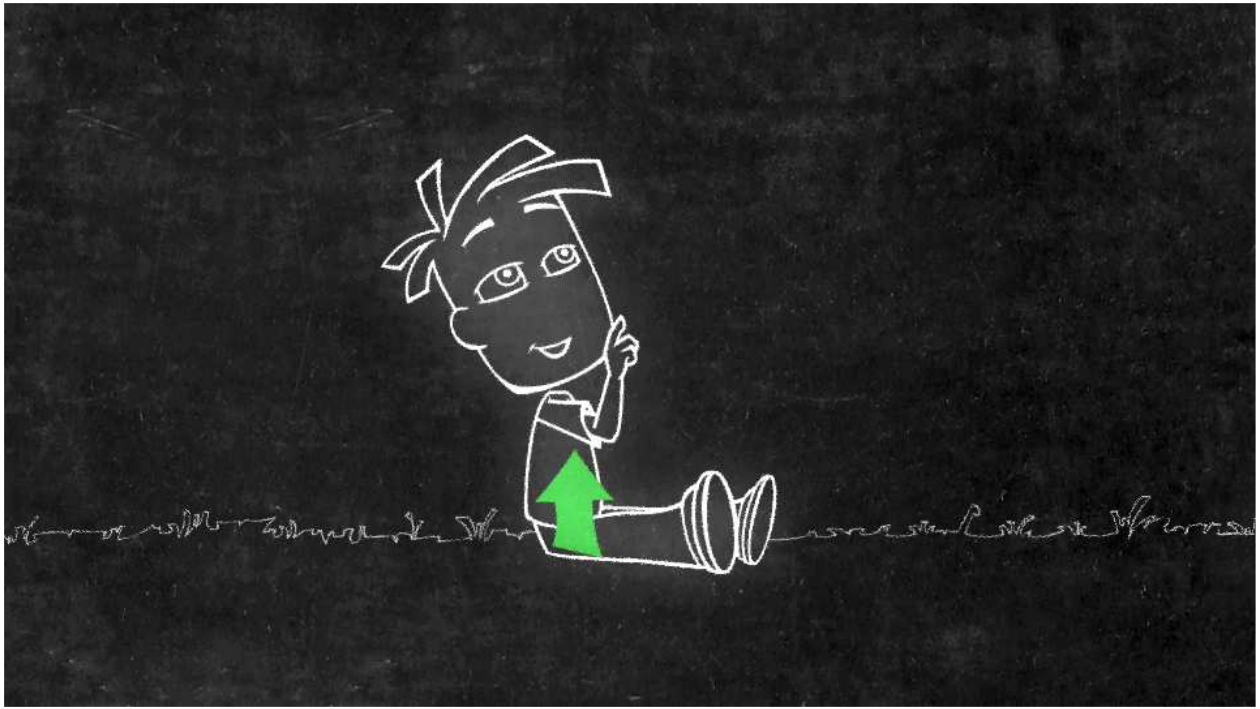


Accelerating Up without Moving Up?

Wouldn't this proposal require the Earth to be expanding, faster and faster?!

The Big Question: How can the ground be **accelerating** up without **moving** up?

Alice & Bob: **What Keeps Us Stuck to the Earth?**



Accelerating Up without Moving Up?

Summary:

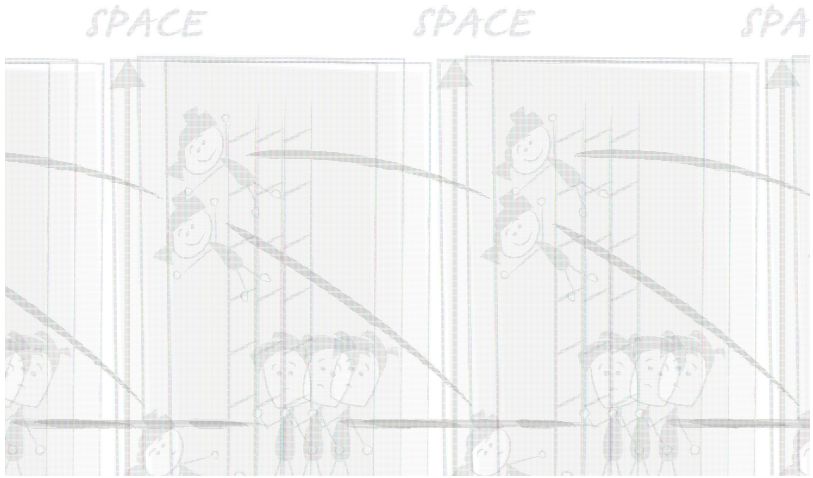
- **Force model** of gravity **failed** (experiment & theory). Scientists were looking for a **new model**
- **Einstein:** Acceleration up **mimics** force down. *Too great of a coincidence to ignore…*
- Einstein just needed to find a way to explain how the ground can be **accelerating up** without **moving up**!

Accelerating Up without Moving Up?

Recall: In special relativity, Einstein had **unified** space & time into **spacetime**. We must think about what is happening not just in space, but in space **and** time, **together**.

Accelerating Up without Moving Up?

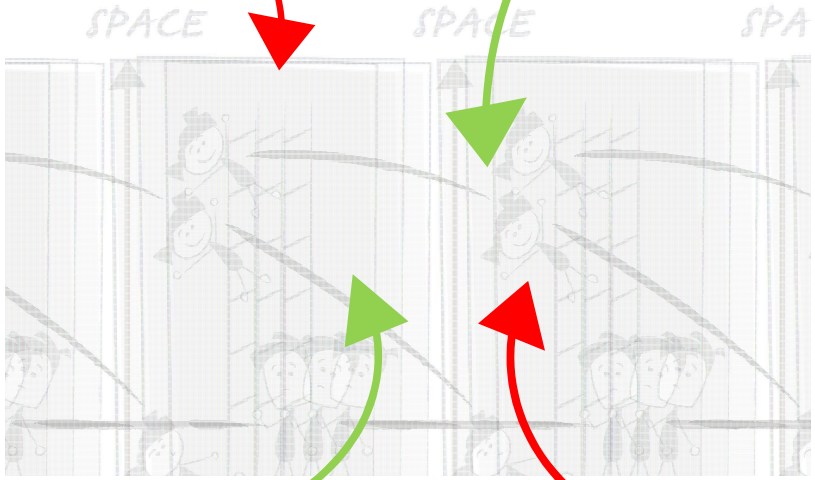
Recall: In special relativity, Einstein had **unified** space & time into **spacetime**. We must think about what is happening not just in space, but in space **and** time, **together**.



According to Newton:

Force
Acceleration
Curved Path

No (Net) Force
No Acceleration
Straight Path



According to Einstein:

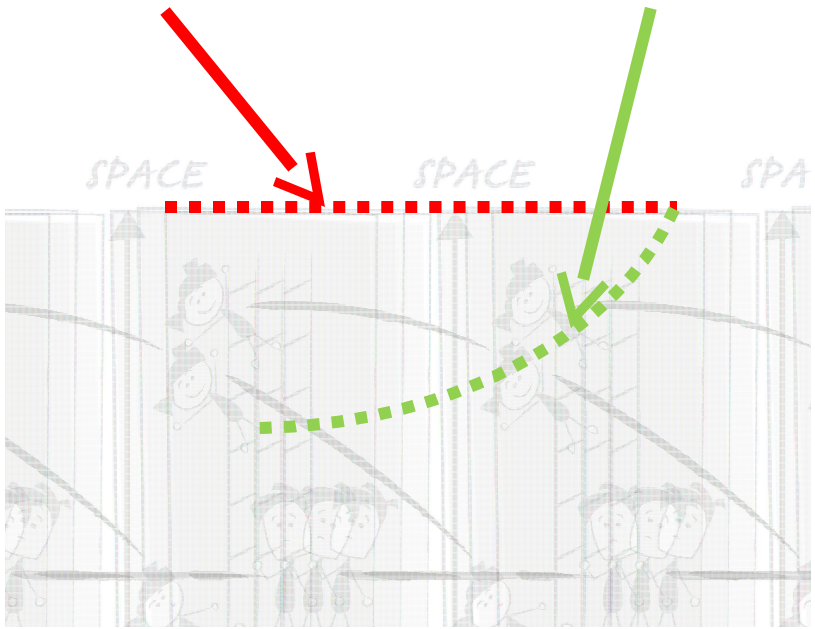
No Force
No Acceleration
Straight Path

Force
Acceleration
Curved Path

Accelerating Up without Moving Up?

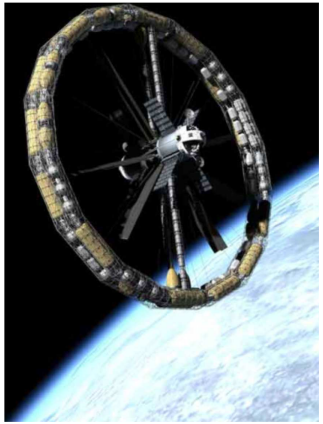
Stay straight (no acceleration)…
but fall to the ground?

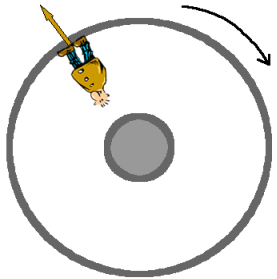
Curve up (accelerate up)…
But not *move* up?



Accelerating Up without Moving Up?

How might this be possible?

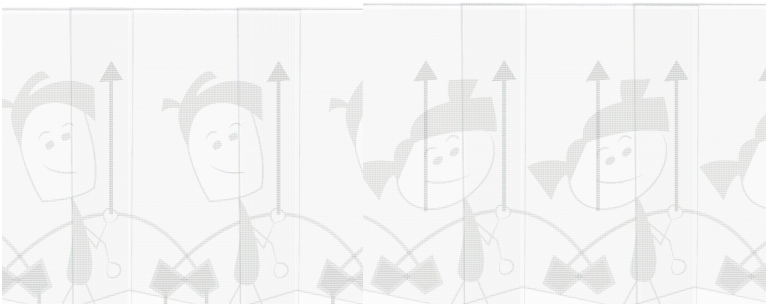




- In special relativity, Einstein showed that **artificial gravity** in a rotating space station is associated with **warping of space** and **warping of time**. The **same is true** for the **artificial gravity** in our accelerated room.

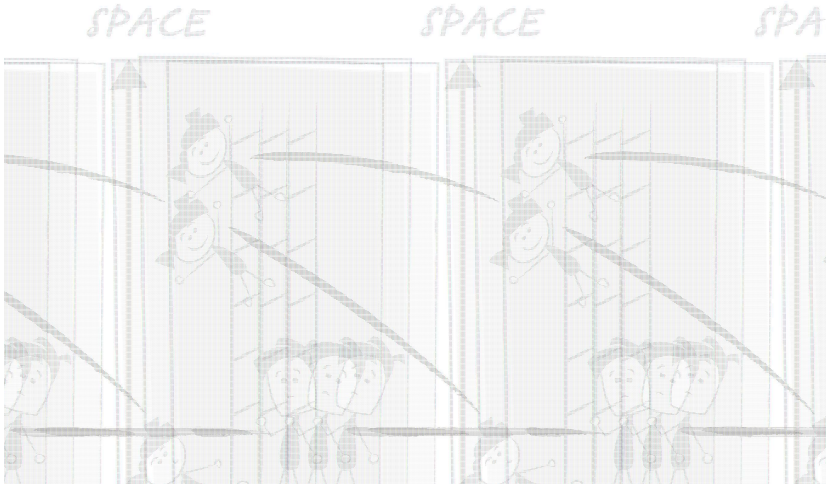
- **Clue:** Maybe **real gravity** is not a force, but a **warping of spacetime**.

- Maybe we can achieve “accelerating up without moving up” (and “not accelerating down but still falling down”) by drawing our diagram not on a **flat surface** (flat spacetime) but on a **curved surface** (curved spacetime)!



Accelerating Up without Moving Up?

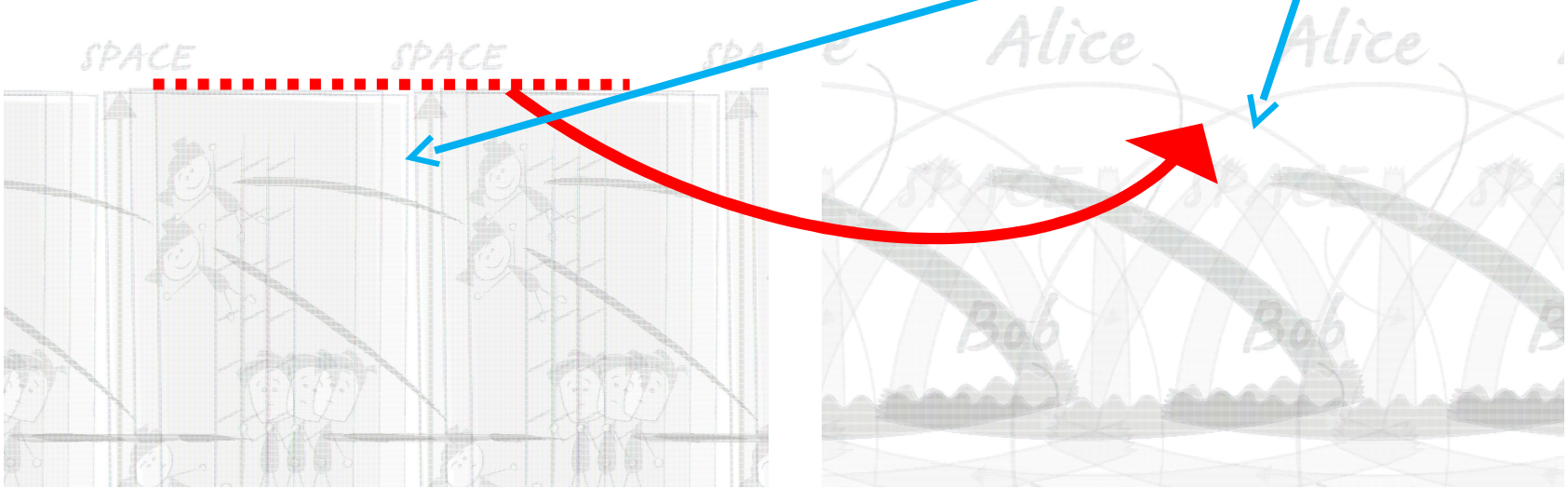
Draw the diagram on a curved surface!



Alice's path *stays straight* (no force, no acceleration)

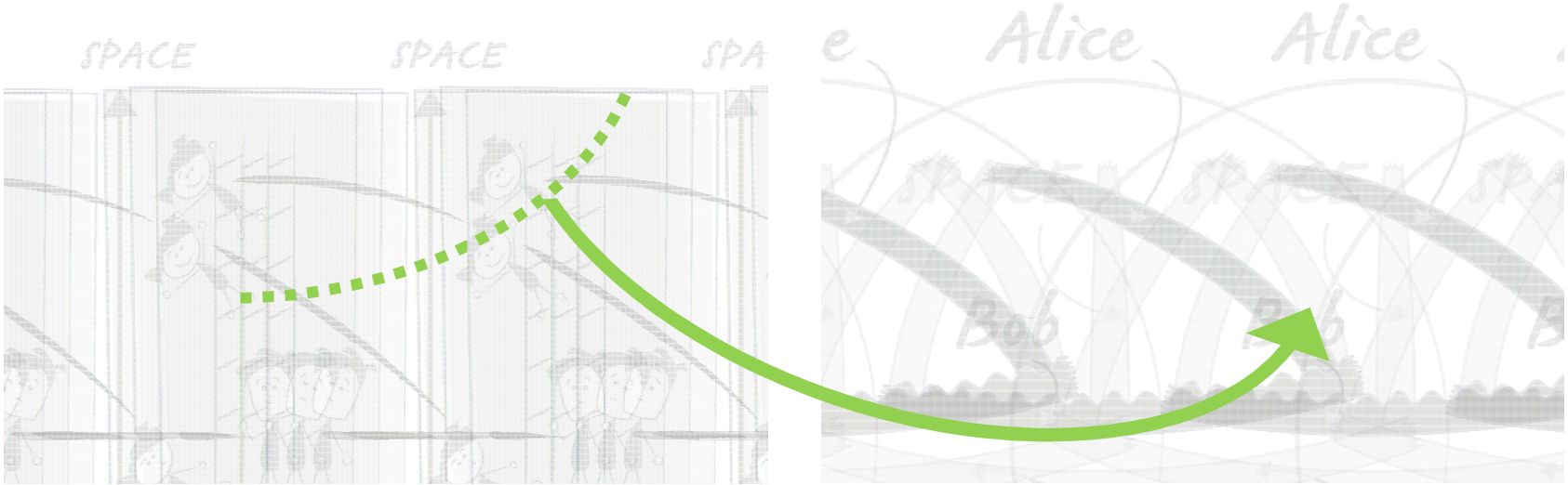
…and yet she is *falling* from top to bottom of ladder!

Both models explain Alice above center of ladder in middle snapshot!



Bob's path *curves up* (he feels upward force & acceleration)

…and yet he is not *moving* up!



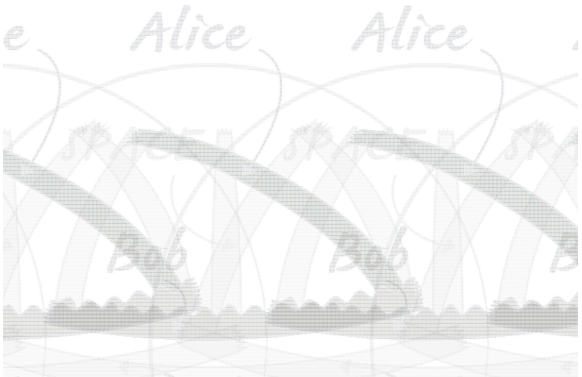
Curved spacetime solves the problem!

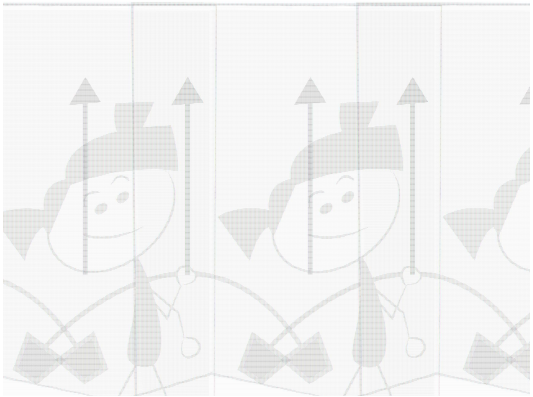
Curved spacetime solves the problem!

Curved spacetime makes it possible for the ground to be continually **accelerating up** without **moving up**!

In the curved spacetime model, the **real** gravity we experience on Earth is ***identical in nature*** to the **artificial** gravity Alice experiences in her room that is accelerating up in empty, gravity-free space.

Weird as it may sound, the curved spacetime model of gravity is ***logically possible***. It ***could be true***. How could we **test** it?

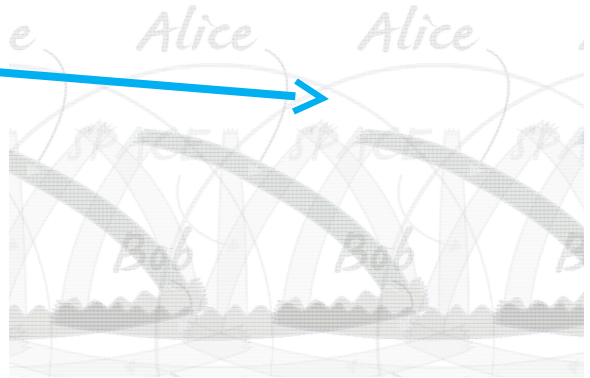


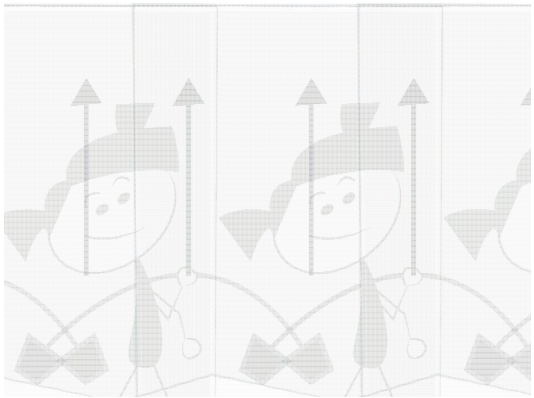


Testing the Curved Spacetime Model of Gravity

The curved spacetime model already explains **everyday observations**: weight, free-fall, etc.

Key question: does the model predict anything **new**, that we might not have guessed to try to observe?





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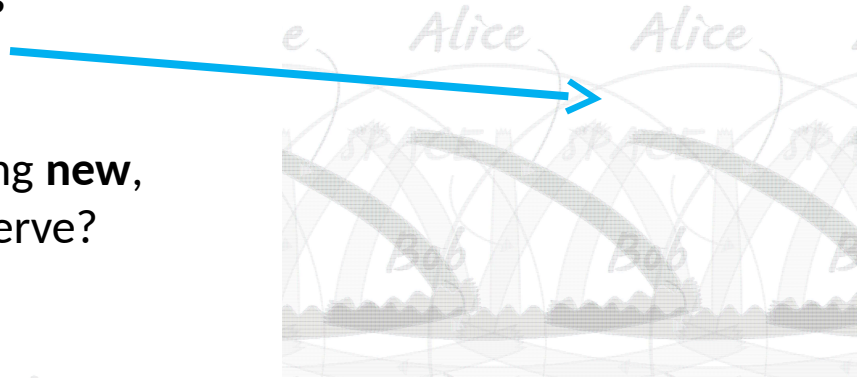
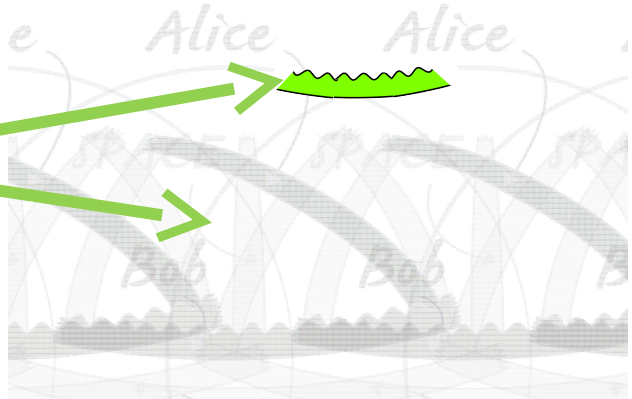
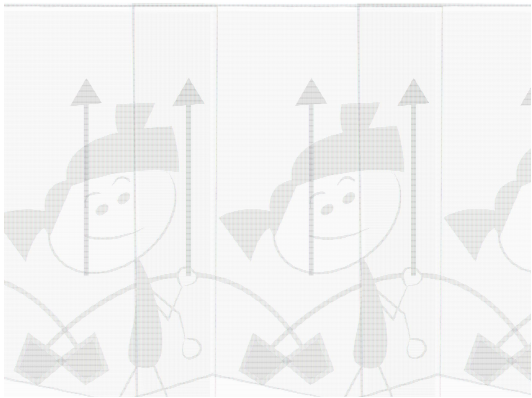


Key question: does the model predict anything **new**, that we might not have guessed to try to observe?

Yes: **Time dilation!**

Elapsed time depends on **height** above the Earth!

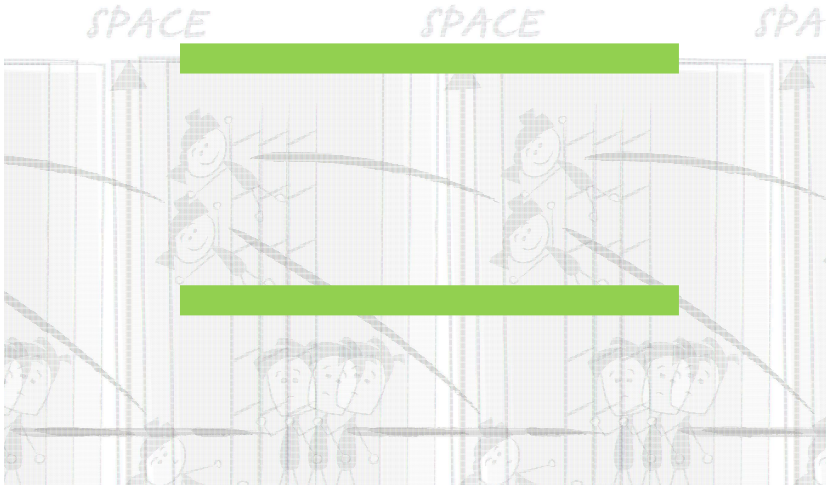


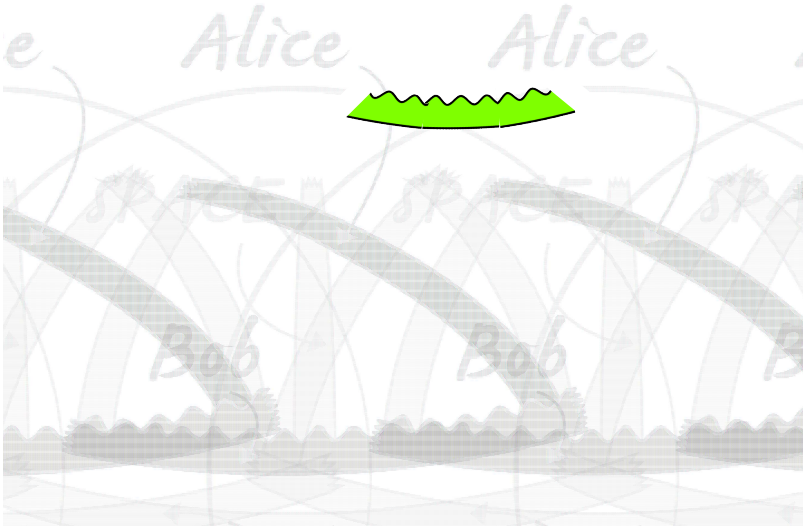


Testing the Curved Spacetime Model of Gravity

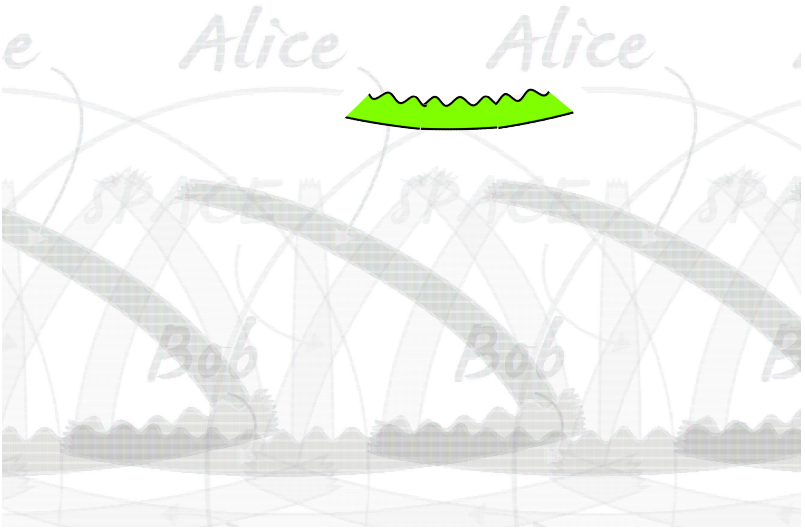
Scientific models cannot be proven **right**, only **wrong**.

Observed time dilation **proves force model wrong**.

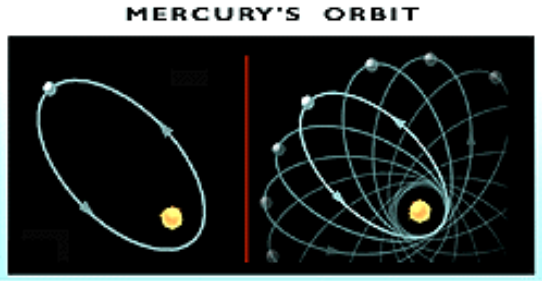




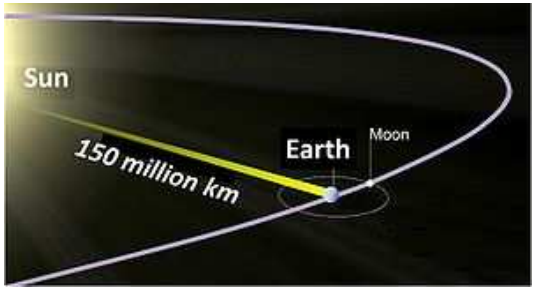
Gravitational time dilation is verified everyday in the functioning of the GPS



The curved spacetime model of gravity also solves other problems…



Experiment: Predicts the ***correct*** orbits

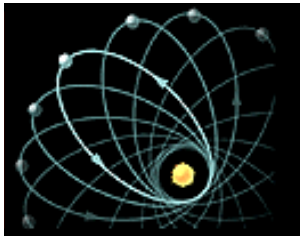


Theory: Does ***not*** violate the speed of light limit

Testing the Curved Spacetime Model of Gravity

There are **many** high precision tests that the curved spacetime model of gravity **passes**, and the force model **fails**. Newton's force model of gravity is **scientifically obsolete**, like alchemy, the Bohr model of the atom, spontaneous generation (e.g., maggots come from dead flesh), etc.

- Einstein's proposed three tests of general relativity ("**classical tests**"):



  - **1: Perihelion precession of Mercury's orbit** (observed by Le Verrier in 1859, explained by Einstein in Nov 1915).
  - Abraham Pais (Einstein biographer): "This discovery was, I believe, by far the strongest emotional experience of Einstein's scientific life, perhaps in all his life. Nature had spoken to him. He had to be right. 'For a few days I was beside myself with joyous excitement'. Later he told Fokker that his discovery had given him palpitations of the heart. What he told de Haas is even more profoundly significant: when he saw that his calculations agreed with the unexplained astronomical observations, he had the feeling that something actually snapped in him."

Testing the Curved Spacetime Model of Gravity

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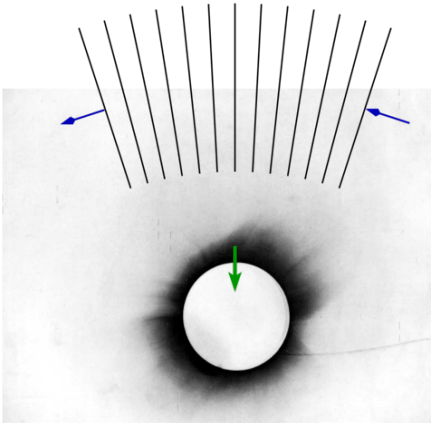
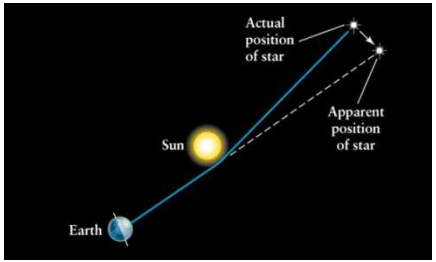
- Einstein's proposed three tests of general relativity ("**classical tests**"):
  - **2: Deflection of light by the Sun** (first *correctly* predicted by Einstein in Nov 1915, observed by Eddington in 1919)
  - Famous solar eclipse expedition just after WW1. People were ready for a "new world;" this news made the front page of most major newspapers. It's what catapulted Einstein to world fame.
  - Asked what if the experiment had failed, Einstein quipped: "Then I would feel sorry for the dear Lord. The theory is correct anyway."





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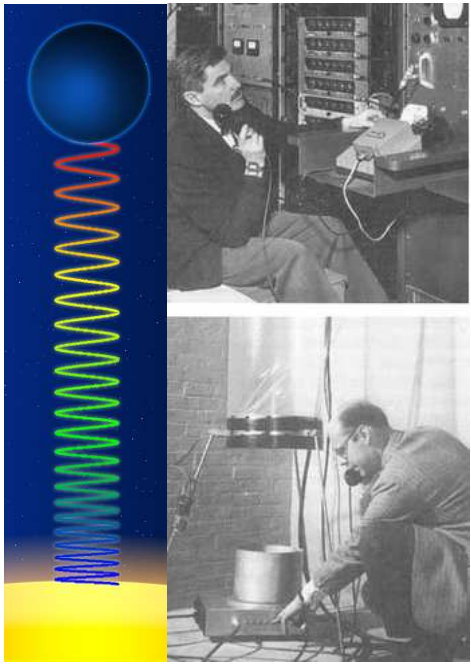
- Einstein's proposed three tests of general relativity ("**classical tests**"):
  - **3: Gravitational redshift of light / gravitational time dilation** (predicted by Einstein in 1907, observed by Pound-Rebka in 1959)
  - Experiment used two gamma ray sources situated at the top and bottom of Harvard University's Jefferson tower, and an extremely sensitive phenomenon called the Mössbauer effect, discovered in 1958.



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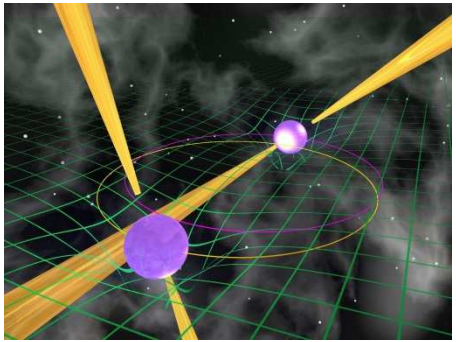
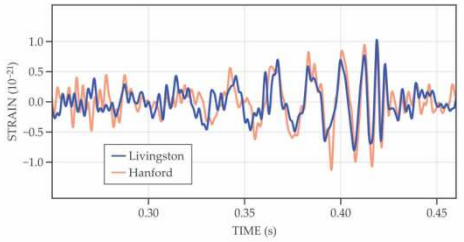
- Many **modern tests** (look these up on your own):
  - Many **weak field** tests within Solar System (lunar and planetary laser/radar ranging; Shapiro time delay, e.g. Cassini mission to Saturn; frame dragging, e.g., Gravity Probe B; daily confirmation via GPS; much more accurate versions of the three "classical tests", e.g., gravitational lensing effects of all sorts; etc.)



  - Many **strong field** tests: Binary pulsars, e.g., Hulse & Taylor: indirect evidence of gravitational waves; Advanced LIGO direct detection of gravitational waves and binary black holes, announced Feb 2016; Event Horizon Telescope; cosmology!



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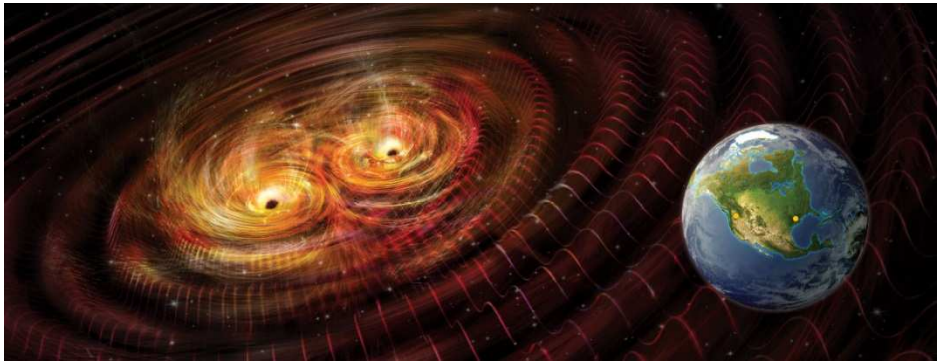
- The **direct detection** of **gravitational waves** is particularly spectacular.

- When a gravitational wave passes by, masses freely floating in a ring shape experience NO FORCE (gravity is not a force) and NO ACCELERATION; instead, the amount of space between them changes with time.

- It is **exactly the same** as the expansion (or contraction) of space in the cosmological context. Space is **not** just a backdrop: it is a **dynamical player**, like everything else!



- This is **essential for free energy & life**!!

Accelerating Up but not Moving Up—Revisited

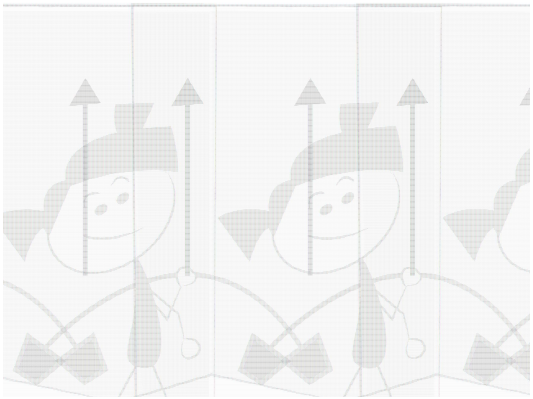
- Science **changes our perspective**—our understanding of the **ultimate nature of reality**, sometimes dramatically.

- General relativity turned **upside down** our understanding of our everyday experience of gravity on Earth:

  - The mass of the Earth does **NOT** pull down on objects.

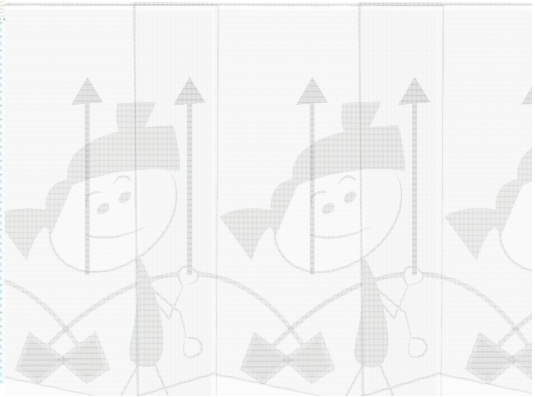
  - The mass of the Earth **curves spacetime** so the ground (and everything standing on it) is <u>literally</u> **accelerating up without moving up**. We experience this acceleration via weight, free-fall, etc.

- What "feels" right is **irrelevant**. *Experiment is the judge*.

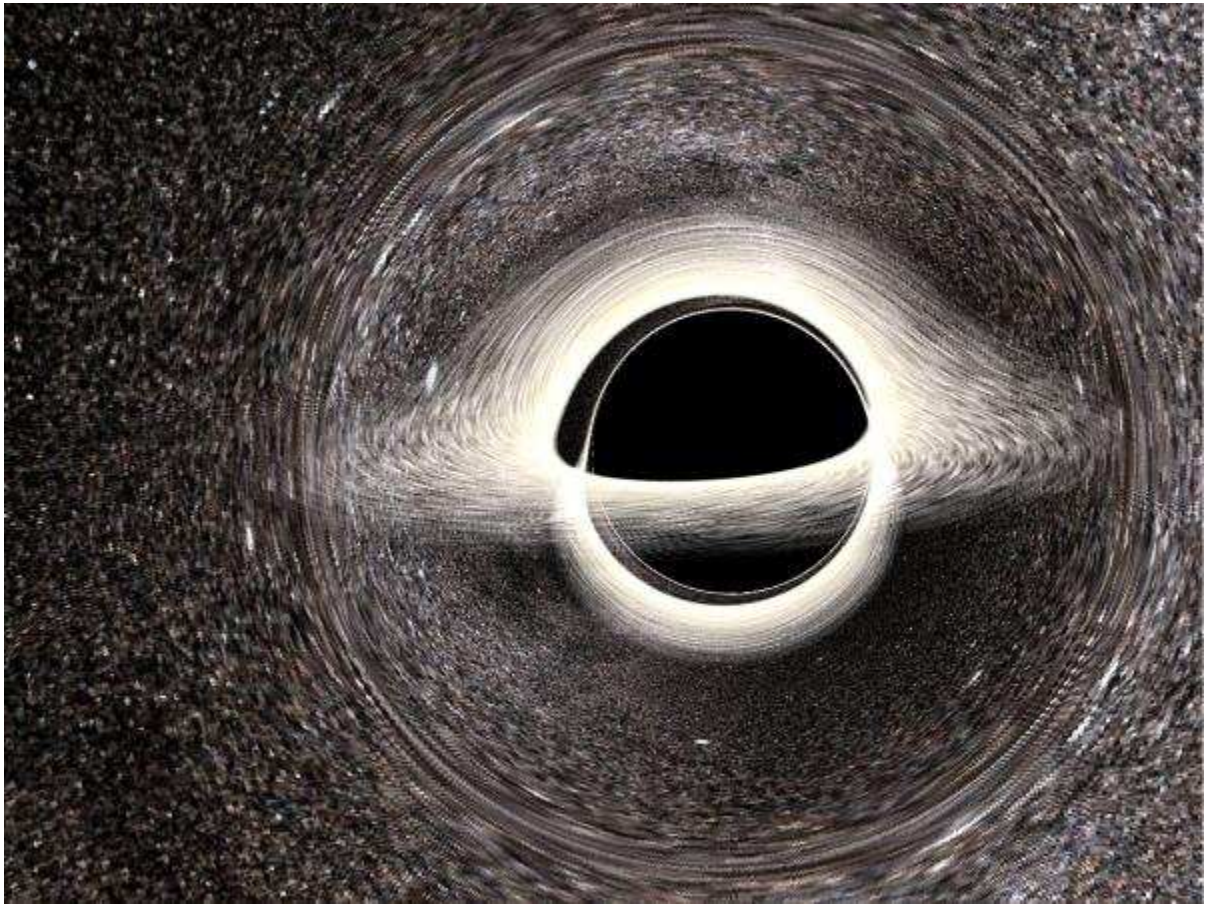


Accelerating Up but not Moving Up—Revisited

- Making sense of **accelerating up without moving up**:
  - Compare Bob's path to a straight path (dropped apple)
  - What force is causing the ground to accelerate up?
  - Straight path between Bob's endpoints (tossed apple)
  - Analogy with centripetal acceleration
  - Comparison with an accelerating rocket in deep space



Black Holes

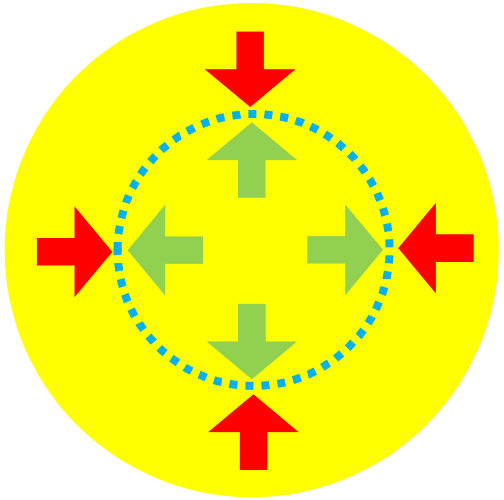


Scientifically accurate (GR ray tracing) image of what a black hole (with an accretion disk, and against a background of stars) would look like.

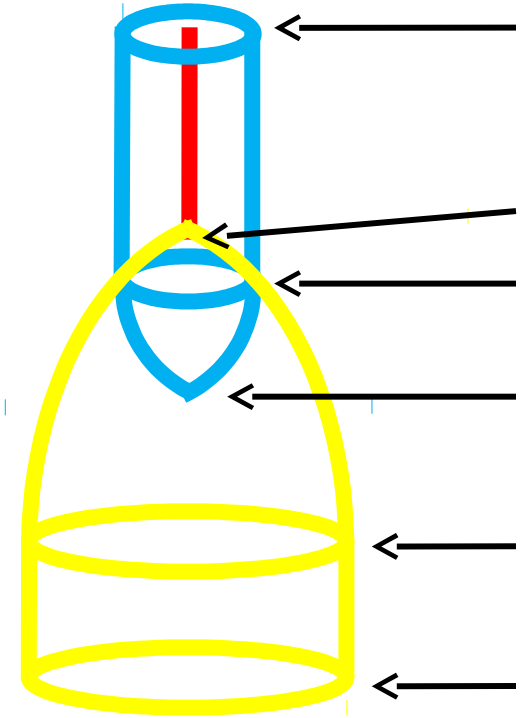
As the most extreme prediction of general relativity, black holes are a good window into the ultimate nature of reality (in a non-quantum context).

Combined with quantum ideas, black holes have led to the **holographic principle**, perhaps our deepest insight into reality…

- Black hole formation from stellar collapse



Star in equilibrium between outward thermal pressure and inward gravitational pull

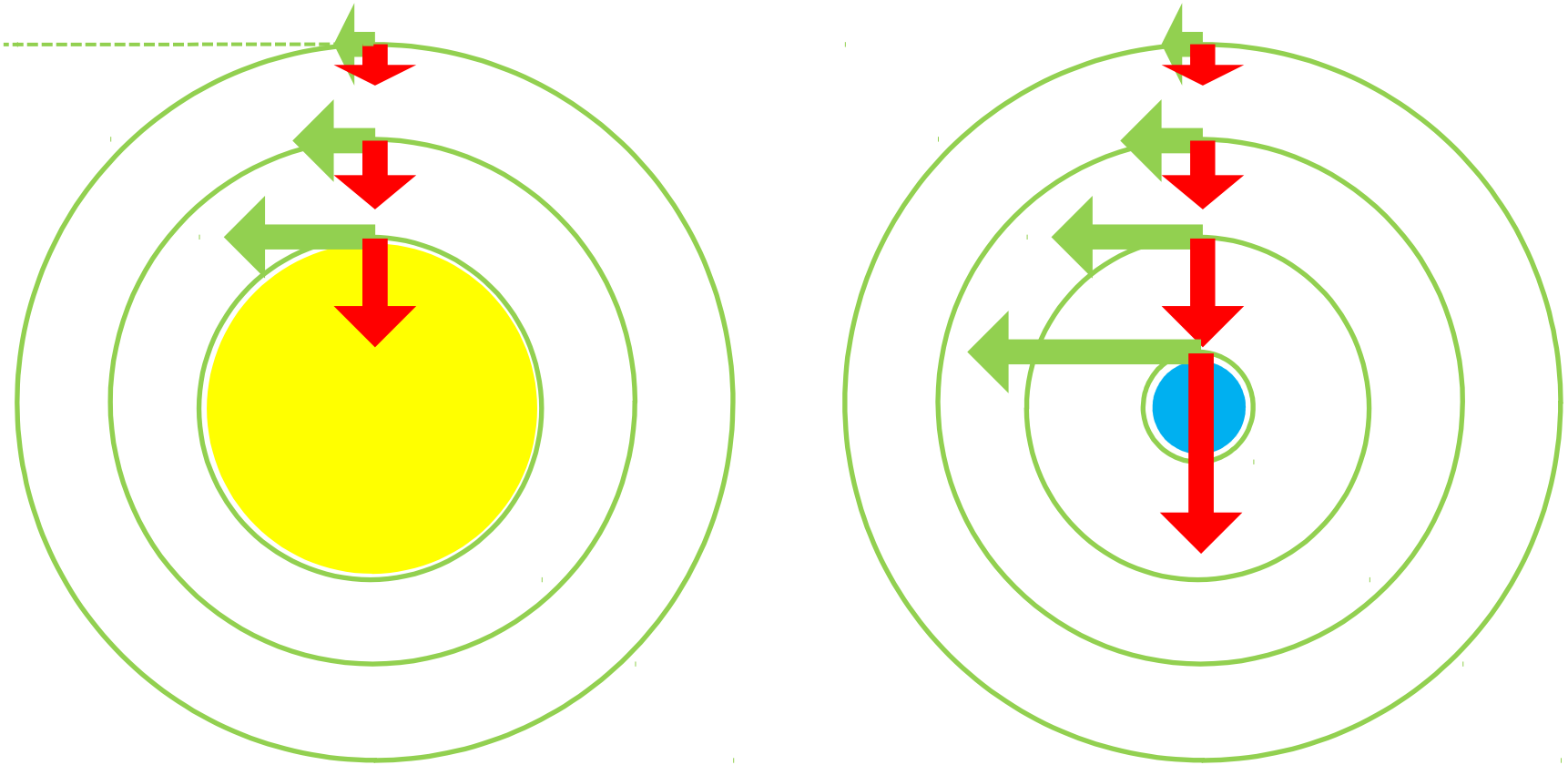


Black Holes

- Birth of a black hole:

Black Holes

- Why strong gravity?



Black Holes

- So a black hole is **NOT** a giant “vacuum cleaner,” “sucking” things in.

- Instead:

  - The same amount of matter has been compressed to a smaller radius, so you can **move in closer** to all the matter, making the gravitational field stronger.

  - But if you are **outside** the radius of the original star, the gravitational field is **exactly the same** as before.

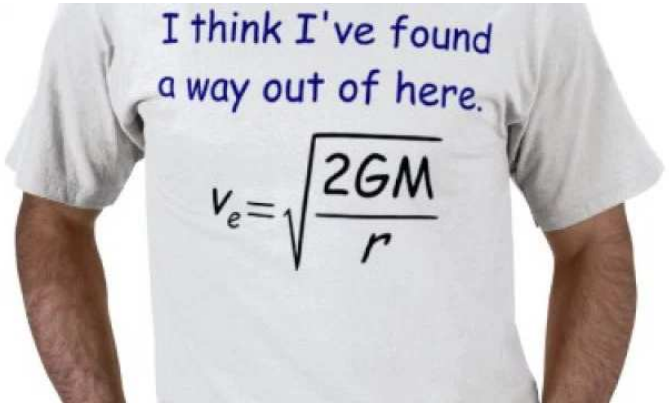
  - If the Sun turned into a black hole, the Earth would continue to orbit **exactly as if nothing had happened**.

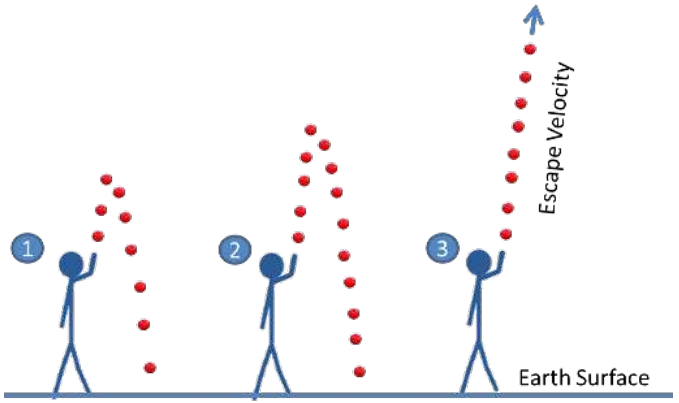
  - But of course, if Earth’s orbit decays (energy is removed from the orbit), it will spiral into the black hole, never to come out again…

- How strong can gravity get?
  - Escape velocity (in Newtonian gravity):

$$v_{\text{escape}} = \sqrt{\frac{2GM}{R}}$$

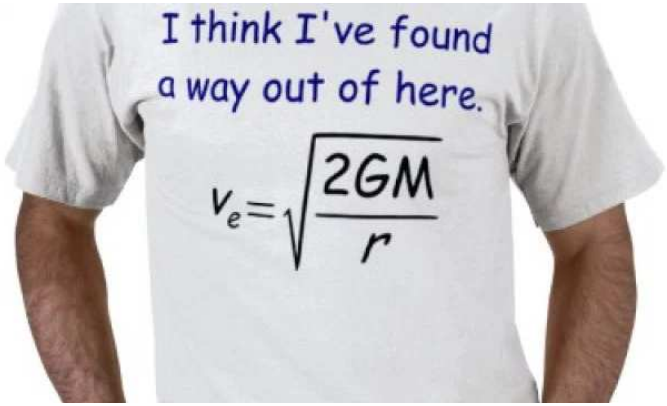
  - From Earth's surface, $v_{\text{escape}} = 11$ km/s.
  - If the mass of the Earth were compressed into a smaller radius, gravity on the surface would get stronger, and v_{escape} would increase.
  - At $R = 8.7$ mm, $v_{\text{escape}} = c$, and nothing could escape the pull of Earth's gravity.





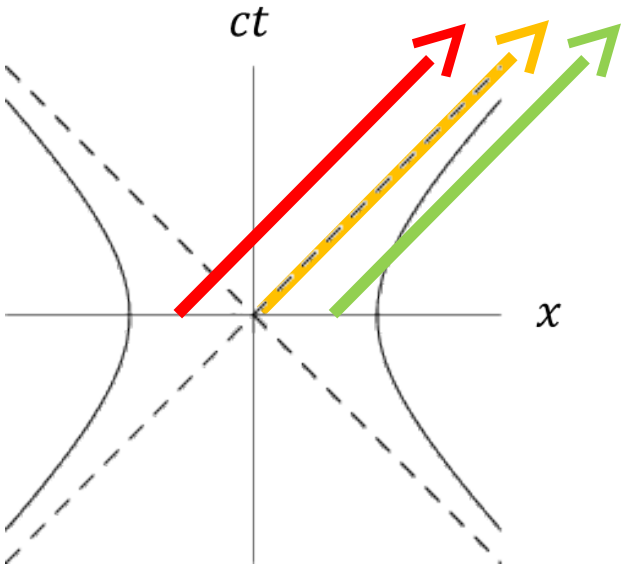
- How strong can gravity get?
  - Set $v_{\text{escape}} = c$ in Newton's formula:

$$c = \sqrt{\frac{2GM}{R}} \quad \Rightarrow \quad R = R_S = \frac{2GM}{c^2}$$



  - Here R_S = "**Schwarzschild radius**". Any mass M, compressed to $R = R_S$, would form a **black hole**. ***Gravity at the surface would be strong enough that nothing, not even light, could escape.***
  - This basic idea of a "**dark star**" was first proposed by **John Michell** in 1783 (Newtonian gravity). GR analogue derived by **Karl Schwarzschild** (1915).

- A **dark star** (Newtonian gravity) and a **black hole** (Einstein gravity) are not the same, though (and that the formula for R_S is the same in both is coincidental)
  - "**Horizon**" in **flat** spacetime (special relativity)



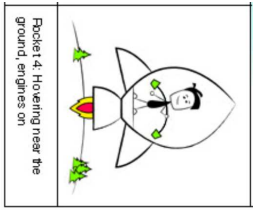
Rocket moving to the right with **constant acceleration**; at rest at $t = 0$, moving faster and faster (limit $v = c$)

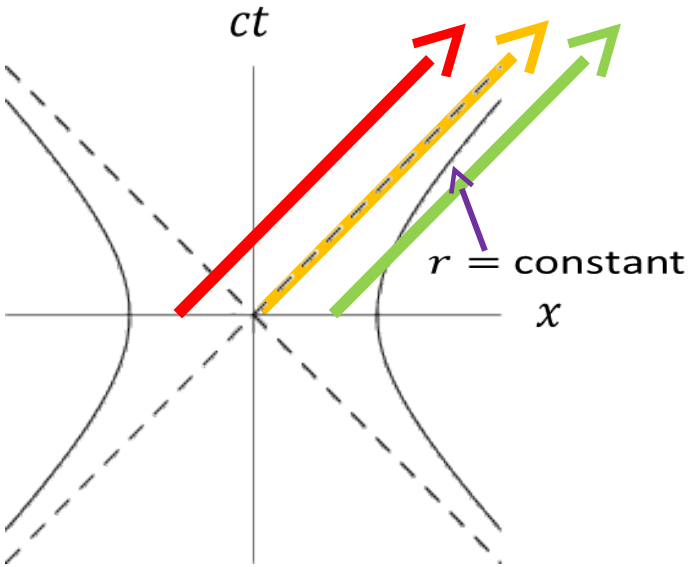
Light ray chasing after rocket, eventually catches up

Light ray chasing after rocket, never catches up; this light source is behind the rocket's "horizon"

Light ray on the rocket's "horizon"

- A **dark star** (Newtonian gravity) and a **black hole** (Einstein gravity) are not the same, though (and that the formula for R_S is the same in both is coincidental)
  - "**Horizon**" in **curved** spacetime (general relativity)





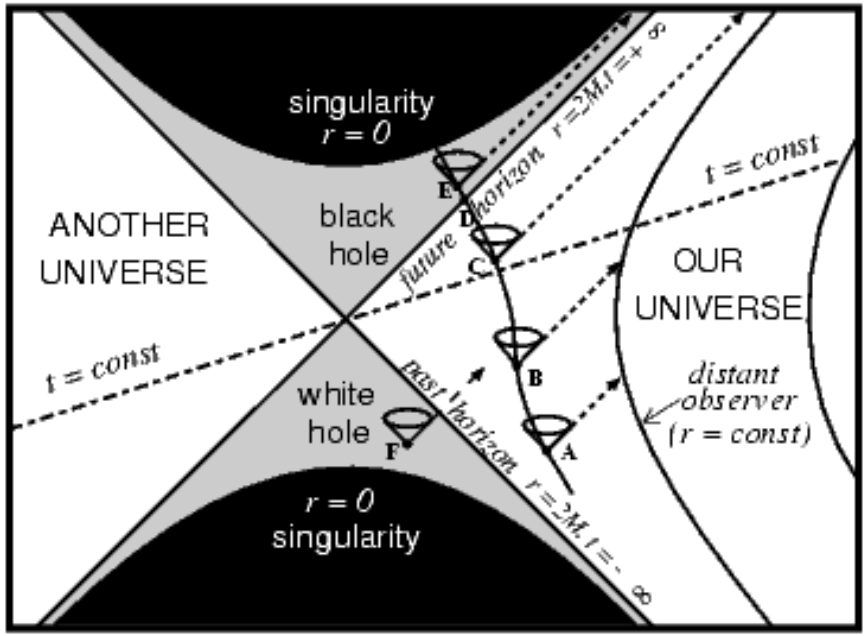
Curved spacetime: **accelerate up without moving up**. Rocket hovering a **fixed distance** from a black hole (or star or planet) under **constant acceleration**.

Light ray shot radially outwards from **above** the "horizon," eventually catches up (and goes to infinity)

Light ray shot radially outwards from **below** the "horizon" never gets out of the black hole

Light ray shot radially outwards from the "horizon" stays **on** the horizon (unlike for Newtonian "dark star")

- A **dark star** (Newtonian gravity) and a **black hole** (Einstein gravity) are not the same, though (and that the formula for R_S is the same in both is coincidental)
  - **Spacetime geometry** of a **black hole**:



observers **hovering** at $r =$ constant; $t =$ time

in-falling observer, sending light signals out

horizon at $R = R_S = \frac{2GM}{c^2}$ ("$2M$" in the diagram)

light rays shot radially outwards from the horizon stay on the horizon. Horizon is radial light surface

singularity at $r = 0$: ∞ curvature; spacetime **ends**

black hole; white hole; another universe; Einstein-Rosen bridge (wormhole); physical black hole

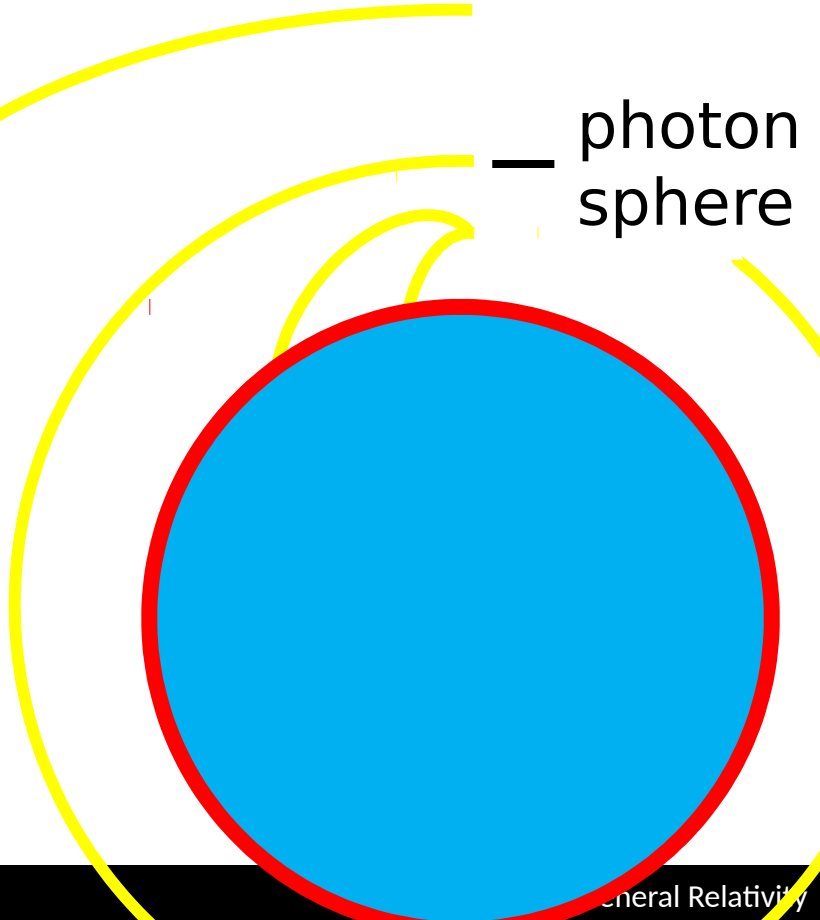
- **“Bending” of Light**

Light rays passing near the event horizon are severely deflected.

Photon sphere: Light orbits the black hole at $R = 1.5\ R_S$. You could see the back of your head!

At rest inside the photon sphere, even some light rays shot *above* the horizontal bend into the black hole. As you approach the horizon, all but the most vertical rays bend back into the horizon.

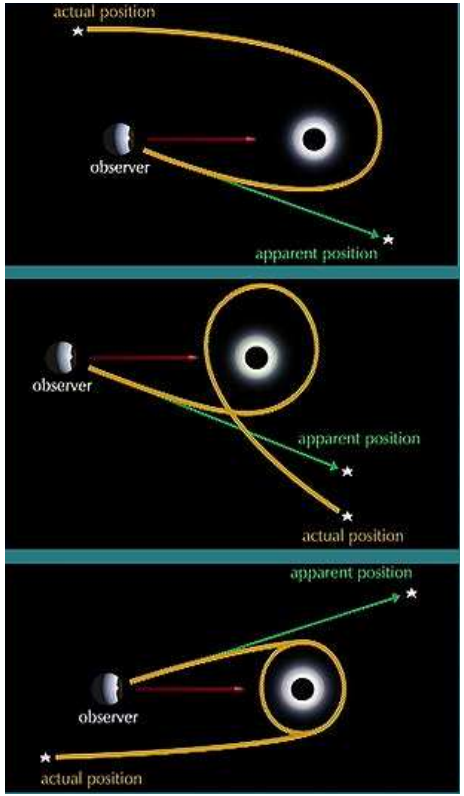
Alternatively, as you approach the horizon, its blackness engulfs you, and the whole sky shrinks into a smaller and smaller disk above your head.



- **“Bending” of Light**

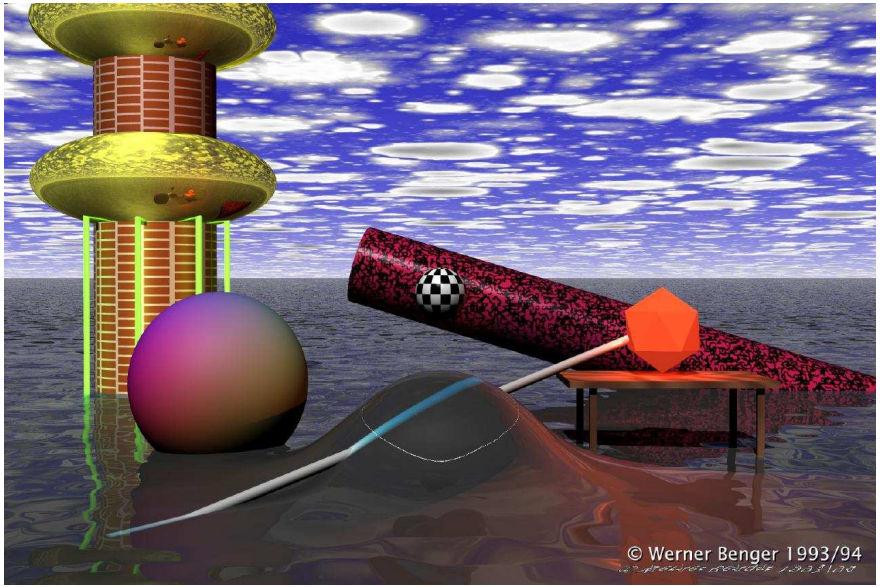
Light rays can orbit several times around before reaching your eye.

Looking near the edge of the event horizon, you see **multiple copies** of the whole sky squeezed into ever narrower “Einstein rings.”

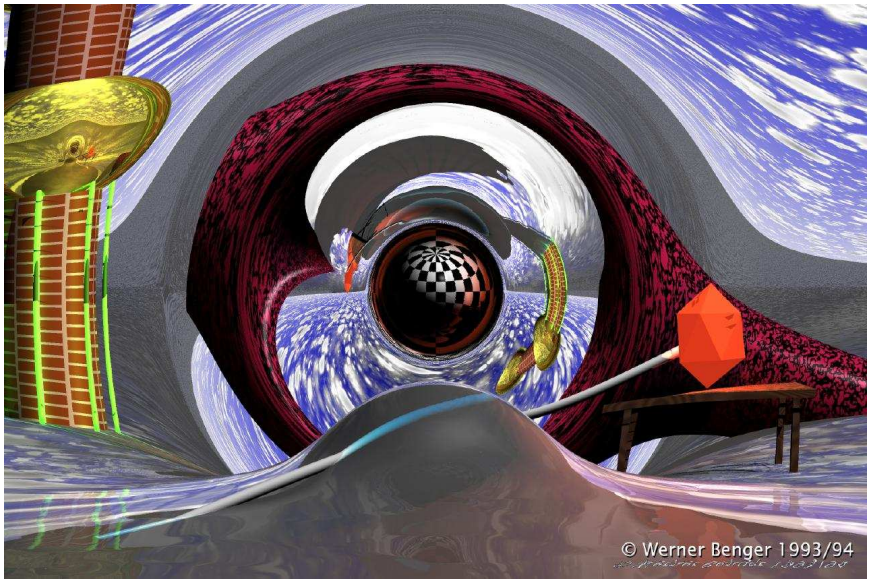


- **“Bending” of Light**

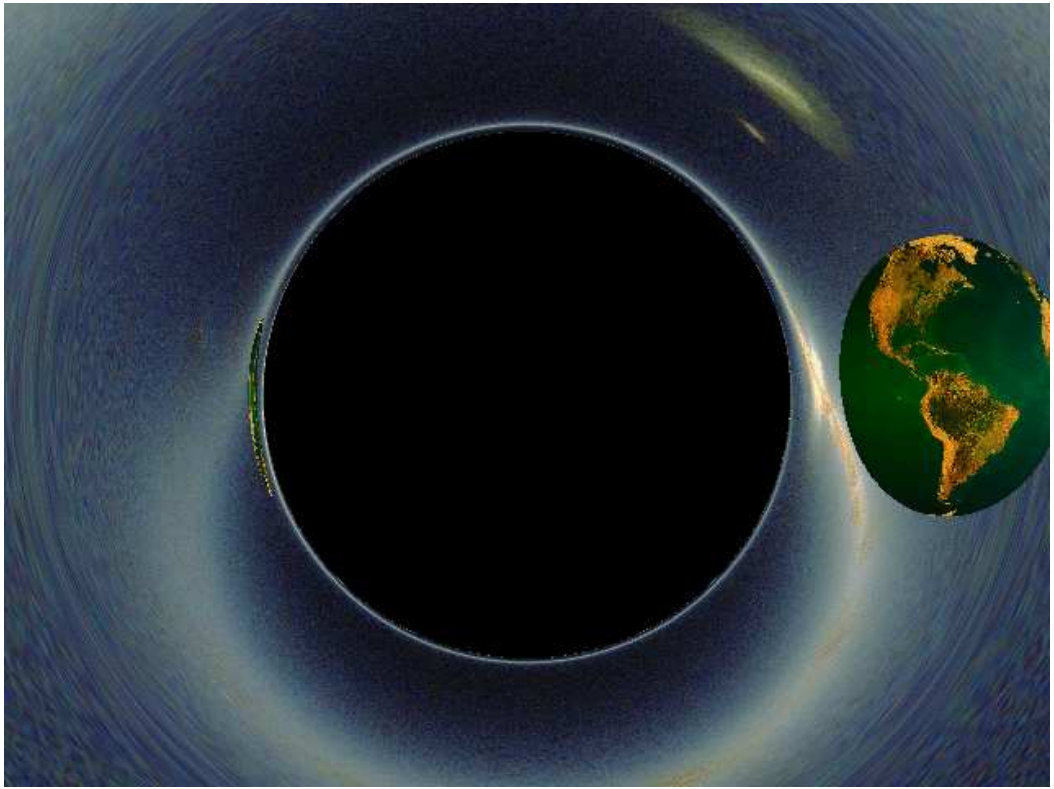
Ray tracing in Newtonian gravity



Ray tracing in Einstein gravity



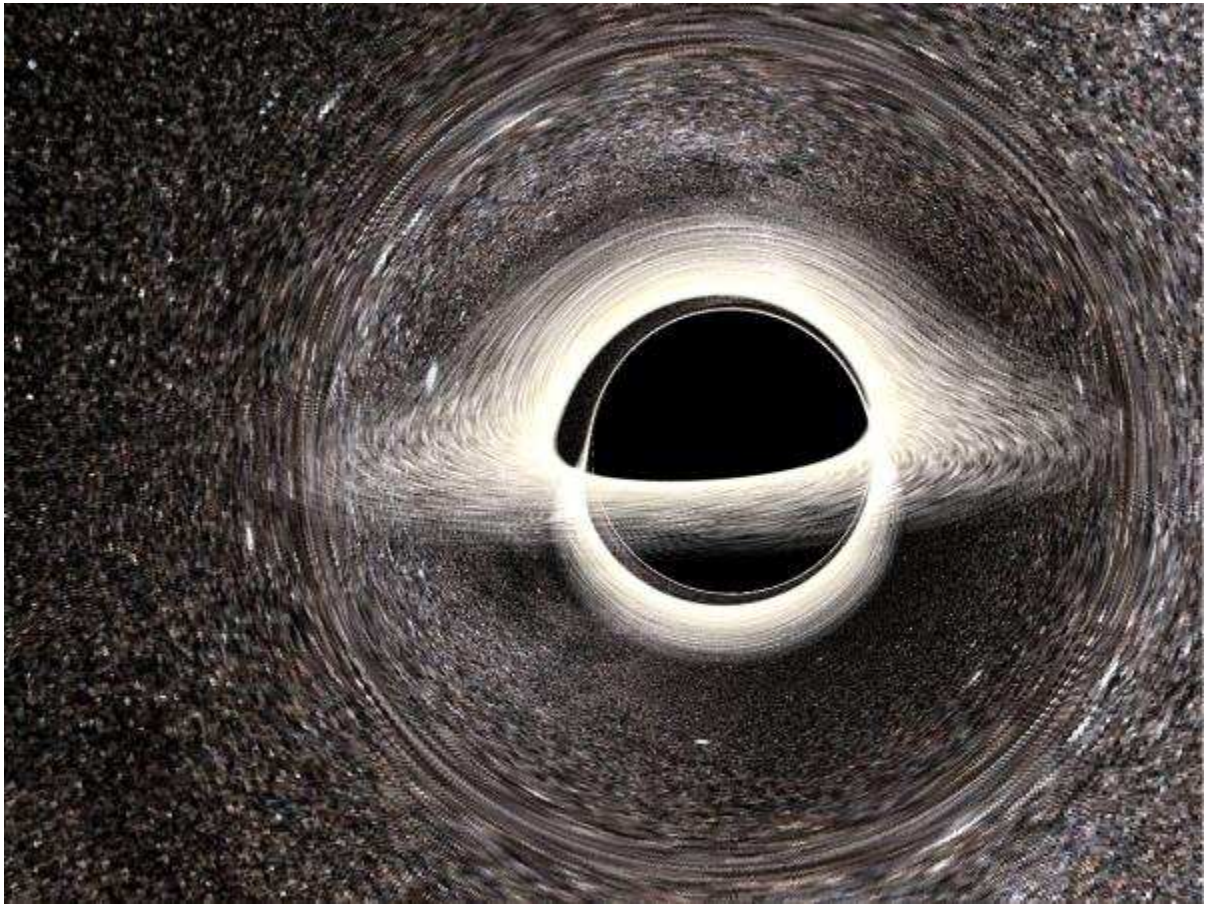
- **“Bending” of Light**



- **“Bending” of Light**

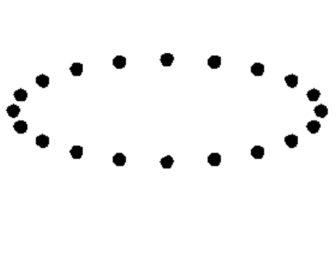
Multiple copies of the whole sky (“Einstein rings”)…

Distortion of the accretion disk (see disk on back side both above and below the black hole)…



- **Falling Into a Black Hole**

  - **Tidal forces:** stretching in length & squeezing in width. These get stronger the closer you approach the BH.



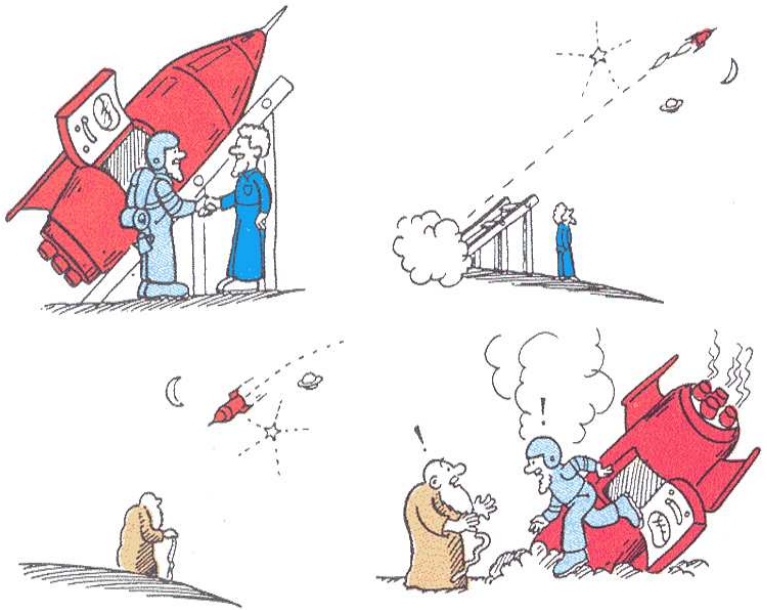
  - Tidal forces at the horizon (between head and toes):
    - ✓ About 1 million g for a 30 solar mass BH (you're dead long before you fall through the horizon). Time to hit singularity ~ 0.0001 s.
    - ✓ About 1 g for a 30,000 solar mass BH (no problem; becomes deadly only closer to the singularity). Time to hit singularity about 0.1 s. (About 1 second for the SMBH at the centre of our galaxy.)

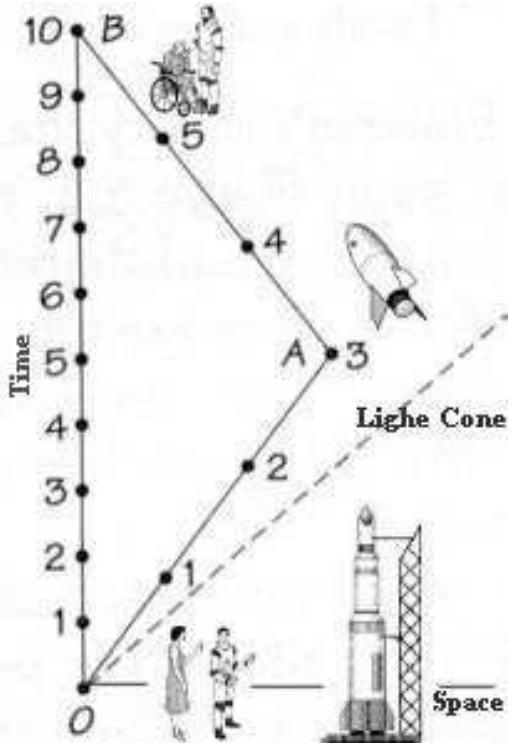
  - Approach singularity: "spaghettification"…like the "Big Rip"

  - Can see the outside universe, but not the singularity…

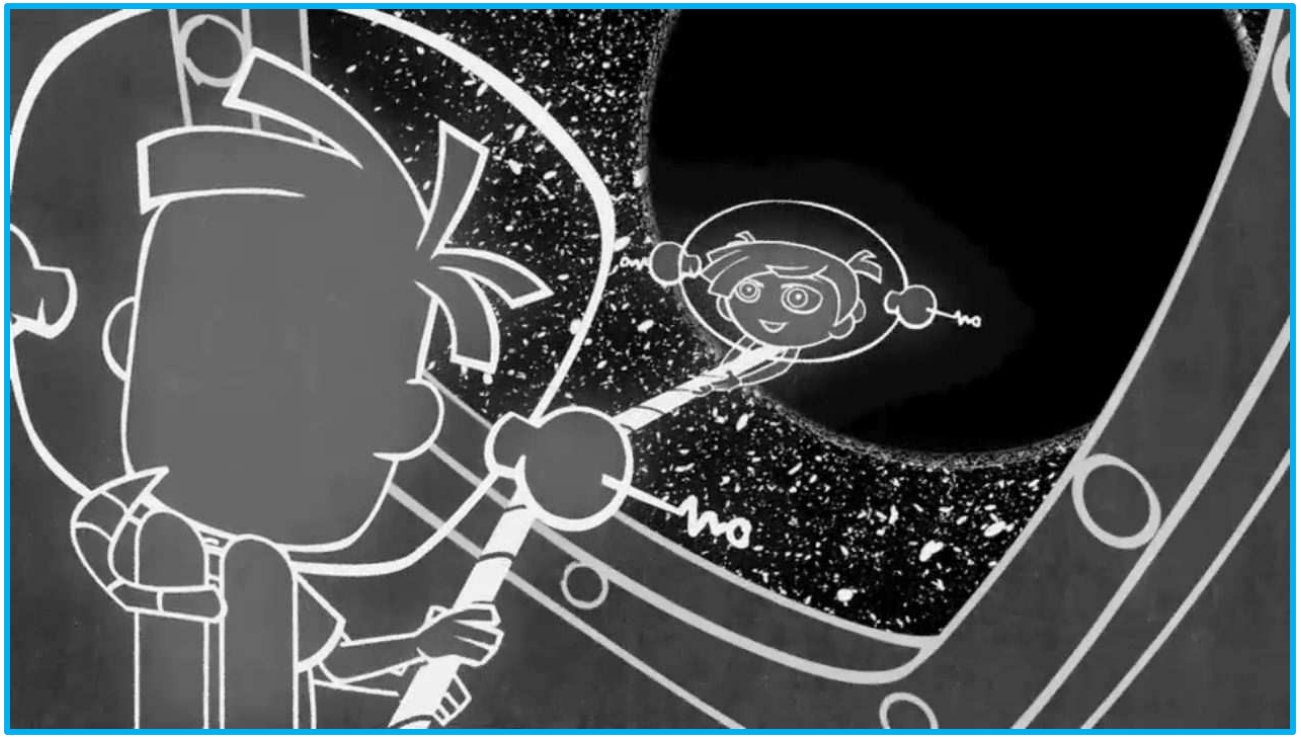
- **Falling Into a Black Hole;** Supercomputer simulations by Andrew Hamilton

Time Travel to the Future is Easy: Using MOTION (SR time dilation)



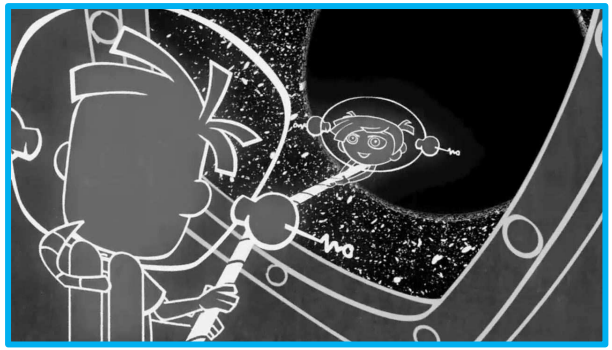


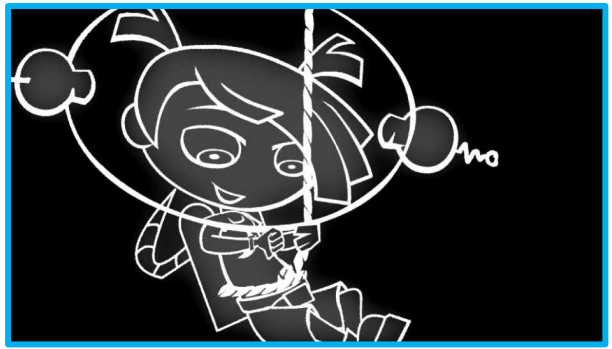
Time Travel to the Future is Easy: Using MASS (GR time dilation)



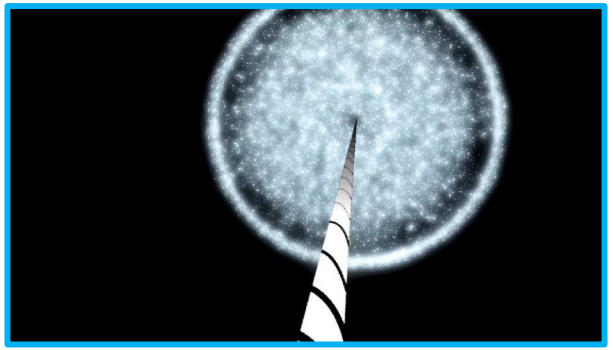
Time Travel

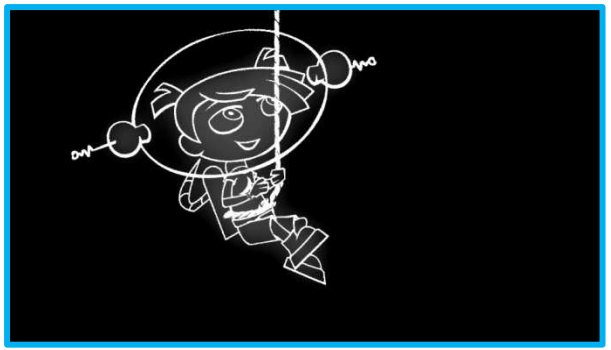
Close to the horizon, time slows nearly to a stop for Alice, **relative** to Bob. But Alice's acceleration also approaches infinity!





Notice also the severe **bending of light**: Alice sees multiple copies of the whole sky in a small disk above her head…





Time Travel to the Past is Tricky

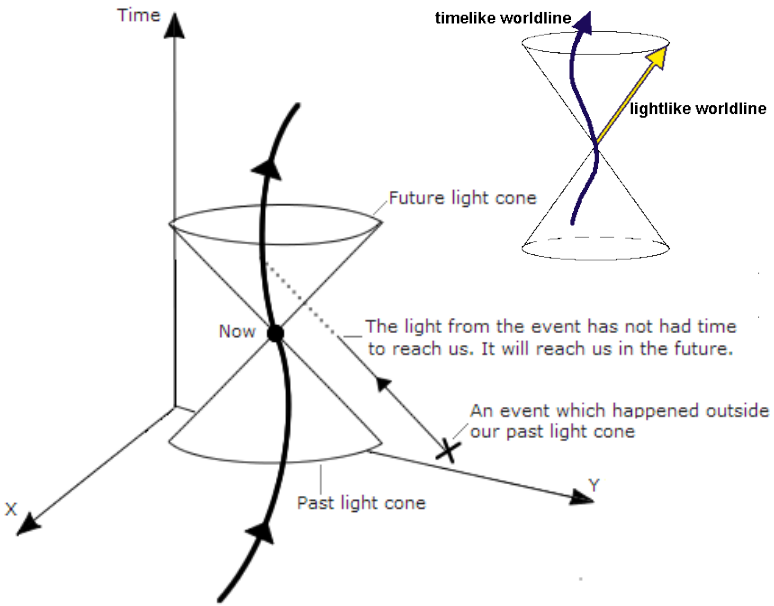
First: The mathematics of general relativity certainly **allows** spacetimes in which it is possible to travel **backwards in time**. *GR itself has no problem with time travel to the past*.

But: There are two **key problems**:

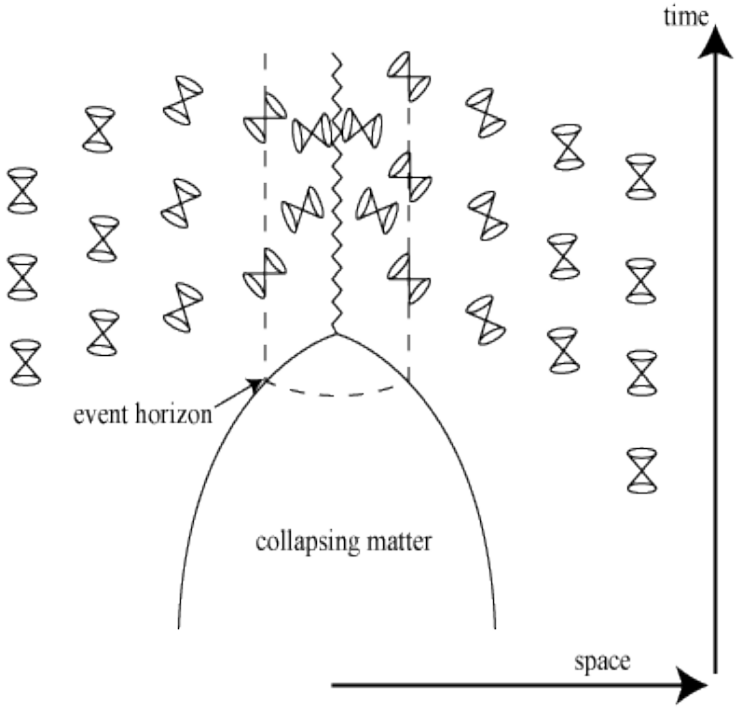
- The **paradoxes** that result (e.g., "Grandfather Paradox")
- Whether a suitable time **machine** could, even in principle, be constructed

We shall see that the **quantum nature** of our universe plays an important role in **potentially solving** both key problems. This will be a natural segue into discussing **quantum mechanics** and, ultimately, **quantum gravity**, a.k.a., a "**theory of everything**"…

Time Travel to the Past is Tricky—Paradoxes

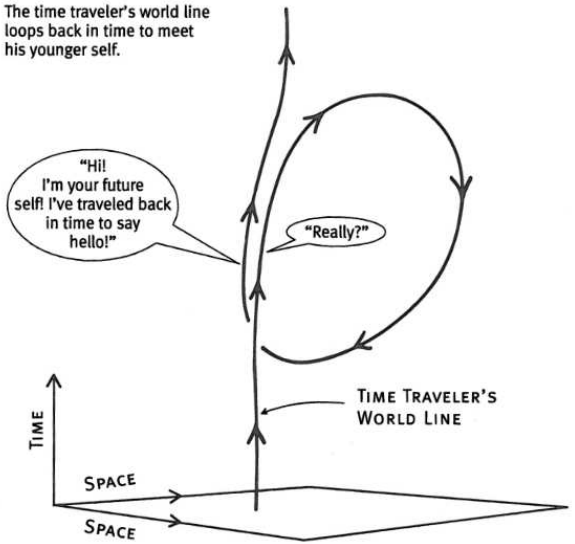


Concept of a “light cone” in SR and GR

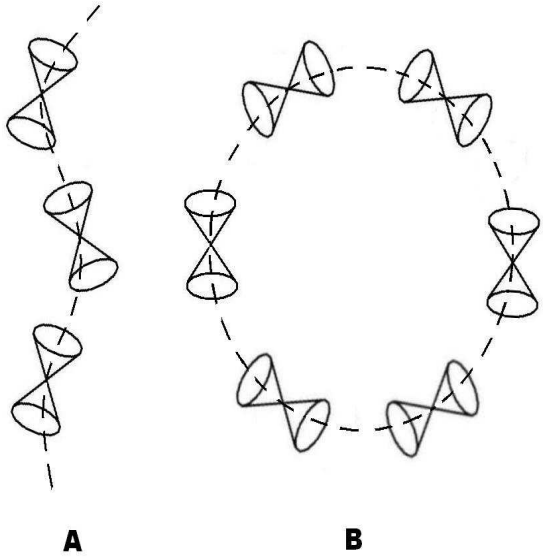


Light cone picture of a black hole

Time Travel to the Past is Tricky—Paradoxes

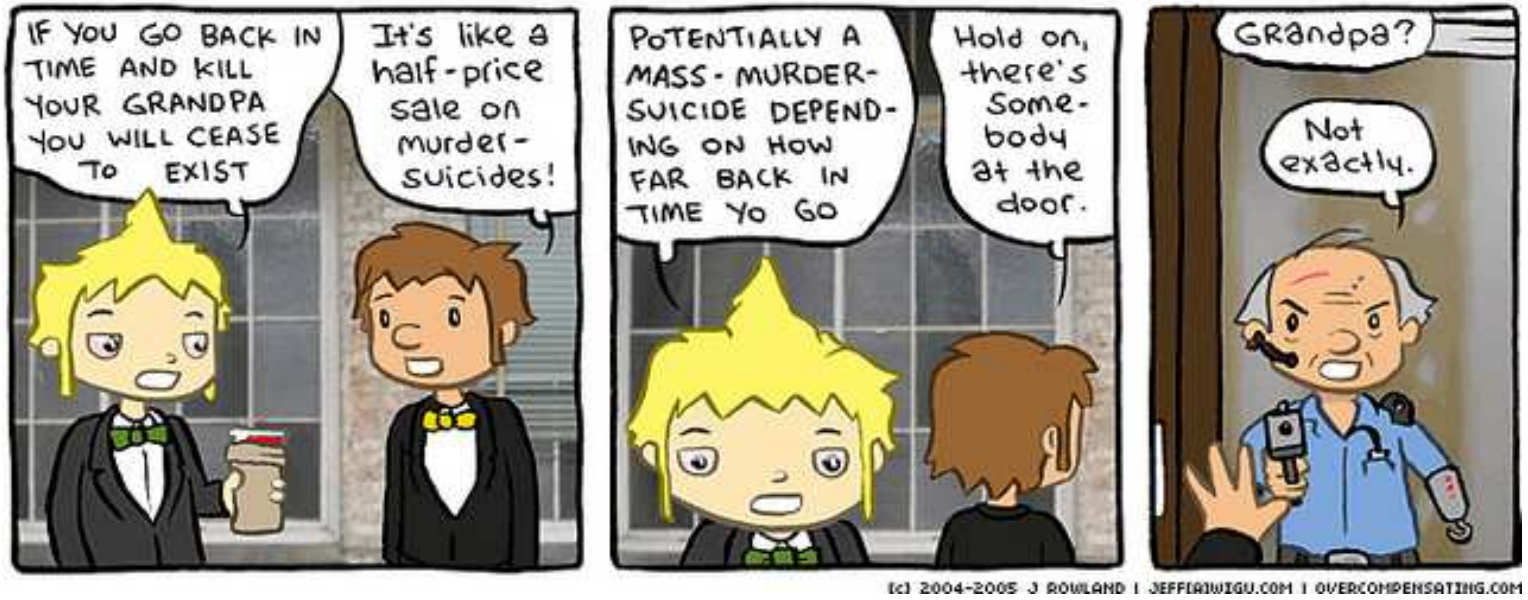


Travelling backwards in time



"Normal" versus "closed" timelike curves

Time Travel to the Past is Tricky—Paradoxes



Problem: Grandfather Paradox

Time Travel to the Past is Tricky—Paradoxes

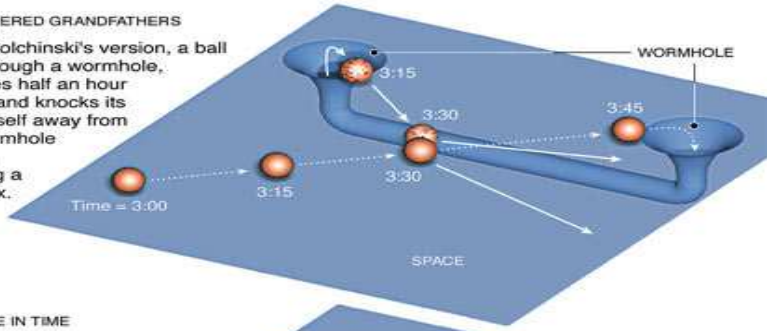
Classical self-consistency resolution:

Eight Ball in the Corner Wormhole

In 1988 a trio of Caltech physicists suggested that a time machine could be constructed in principle, using a wormhole, or short cut through space time, in which the mouths have been manipulated to exist at different times. Does that mean you could go back in time and kill your grandfather, thus short-circuiting your own existence? Dr. Joseph Polchinski suggested that it did, imagining how a billiard ball going through a time machine could cancel itself and create a paradox. Here is how the question was resolved.

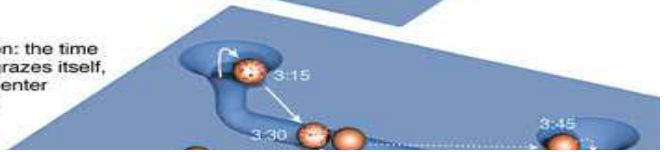
ENDANGERED GRANDFATHERS

In Dr. Polchinski's version, a ball rolls through a wormhole, emerges half an hour earlier and knocks its earlier self away from the wormhole mouth, creating a paradox.



A CIRCLE IN TIME

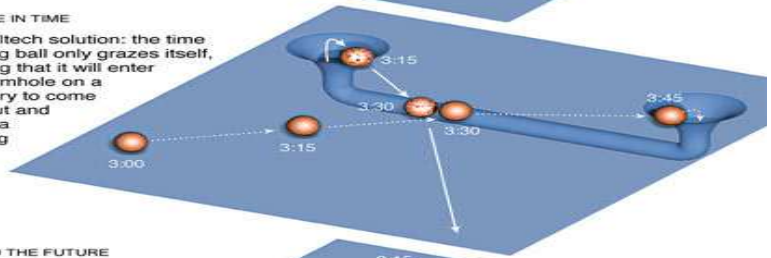
The Caltech solution: the time traveling ball only grazes itself, ensuring that it will enter the wormhole on a trajectory to come back out and



creating a paradox.

A CIRCLE IN TIME

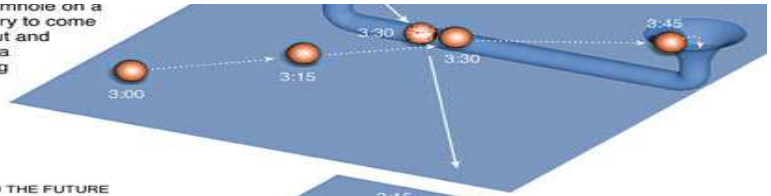
The Caltech solution: the time traveling ball only grazes itself, ensuring that it will enter the wormhole on a trajectory to come back out and deliver a glancing blow.



BACK TO THE FUTURE

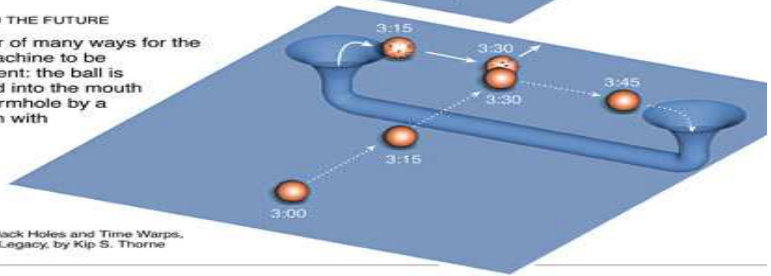
Another of many ways for the time machine to be

the wormhole on a trajectory to come back out and deliver a glancing blow.



BACK TO THE FUTURE

Another of many ways for the time machine to be consistent: the ball is diverted into the mouth of a wormhole by a collision with itself.

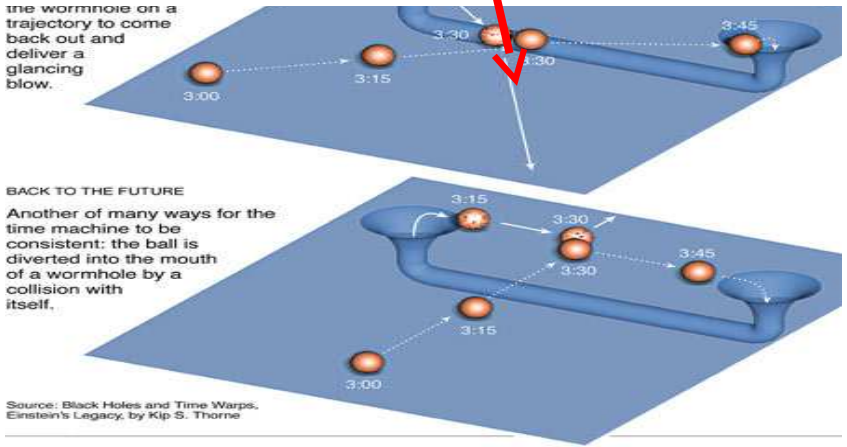


Source: Black Holes and Time Warps, Einstein's Legacy, by Kip S. Thorne

Time Travel to the Past is Tricky—Paradoxes

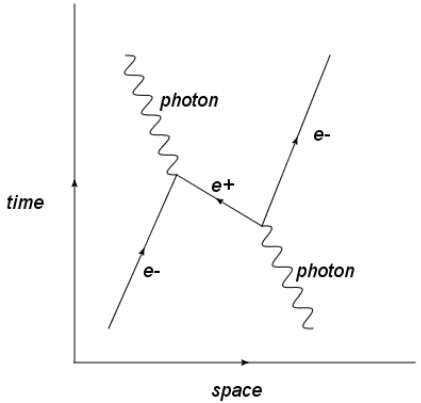
Classical self-consistency resolution:

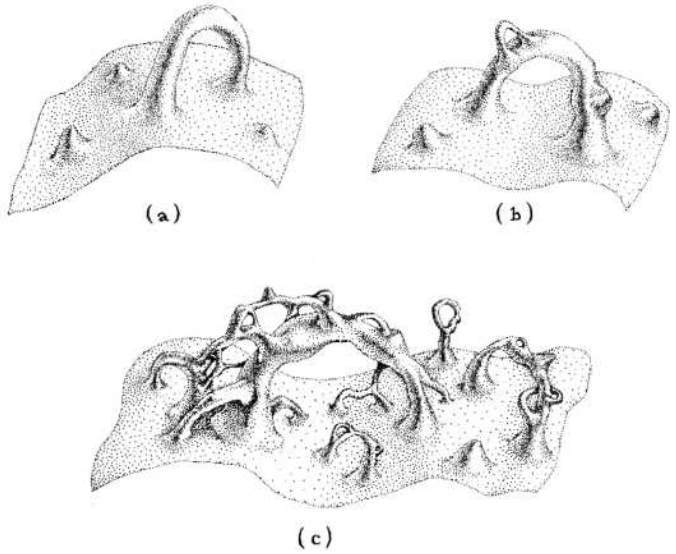
Problem: Although this resolves the paradox, it does so at the expense of violating the "autonomy principle": The ball that returns to the past has **no choice in what it can do**. (Like sci-fi movie where traveller cannot change the past.)



Time Travel to the Past is Tricky—Paradoxes

Quantum to the rescue?





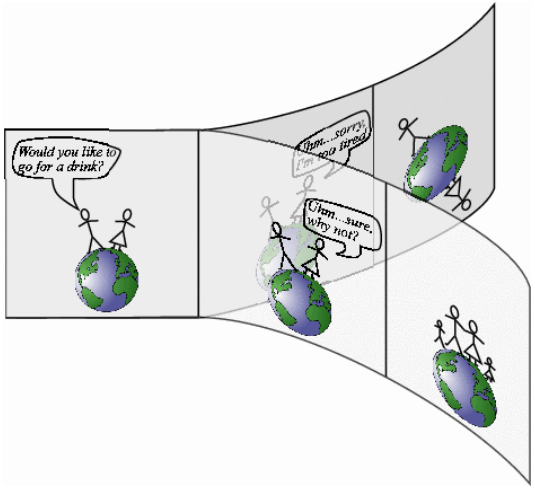
In our quantum universe, an **antimatter** virtual particle travelling **forwards** in time (e^+) is the same as a **matter** virtual particle (e^-) travelling **backwards** in time.

Several approaches to quantum gravity suggest that spacetime has a foam-like submicroscopic structure containing many wormholes and CTCs.

Time Travel to the Past is Tricky—Paradoxes

Quantum to the rescue?

For all we know, subatomic particles may regularly be travelling **both forwards and backwards** in time, all the time. If so, it is obviously not a problem for nature. **How could it <u>not</u> be a problem?**



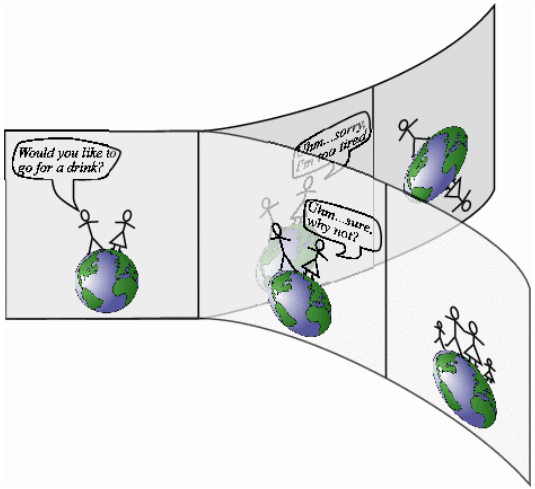
Enter: **Quantum many-worlds interpretation!**

All possible alternate histories and futures are **real**, each representing an actual "world" (or "universe")

Reality is not a single unfolding history, but a many-branched tree. (More on this later…)

Time Travel to the Past is Tricky—Paradoxes

Quantum many-worlds:



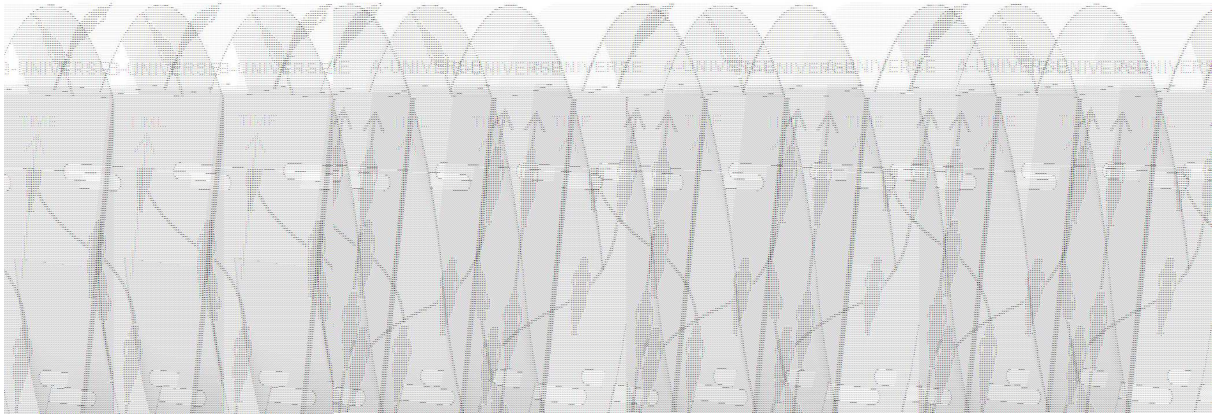
David Deutsch's Idea:

What if the time traveller simply ends up in a different branch of history than the one she departed from?

She disappears from one branch, travels back in time and kills her younger self. There are now two branches: The original, plus one that contains two versions of herself: one dead & one feeling guilty.

Time Travel to the Past is Tricky—Paradoxes

Quantum many-worlds:



E.g.: Alice plans to enter the time machine tomorrow and travel back to today, but resolves that if she emerges from the time machine today, she will not enter tomorrow. She is able to carry out this plan, without paradox. In a B-universe she does not emerge today and so enters the time machine tomorrow. She then emerges today, but in an A-universe, and meets her copy—who does not enter the time machine. From Scientific American, March 1994 (David Deutsch)

Time Travel to the Past is Tricky—Paradoxes

Quantum many-worlds:

2014: Tim Ralph *et al* **experimentally simulated** Deutsch's model of CTCs. Scientific American.

- The results showed that if we **could** find (or construct) a CTC (allowed by general relativity), and it behaved as Deutsch predicts, it could have **remarkable practical applications**:
    - Breaking what is presently considered to be unbreakable **quantum-based cryptography** (by cloning quantum states and circumventing the Heisenberg Uncertainty Principle);
    - Performing **very powerful information-processing tasks**, much more than we believe classical or even normal quantum computers could do. (More on this later…)

Time Travel to the Past is Tricky—Paradoxes

Quantum many-worlds:

2014: Tim Ralph *et al* **experimentally simulated** Deutsch's model of CTCs. Scientific American.

- **Ralph:** "It's intriguing that you've got **general relativity predicting these paradoxes**, but then you consider them in quantum mechanical terms and the **paradoxes go away**...It makes you wonder whether this is important in terms of formulating a theory that **unifies** general relativity with quantum mechanics."

  ▭ this is our ultimate goal...

Time Travel to the Past is Tricky—Paradoxes

Summary:

- General relativity **allows** time travel to the past, but **without quantum mechanics** (i.e., a **classical** picture of reality) it results in **insurmountable logical paradoxes**.

- It appears that travelling backwards in time may be happening all the time in our *actual*, **quantum universe**, at least in the submicroscopic world of elementary particles.

- Indeed, the **many-worlds interpretation** of quantum mechanics suggests that all time travel paradoxes can be readily resolved. The paradoxes are just an artifact of having the **wrong picture of reality** (classical, versus quantum).

Time Travel to the Past is Tricky—Machines

Okay, maybe we've solved the paradoxes problem. The next step is to actually construct a time machine. How?

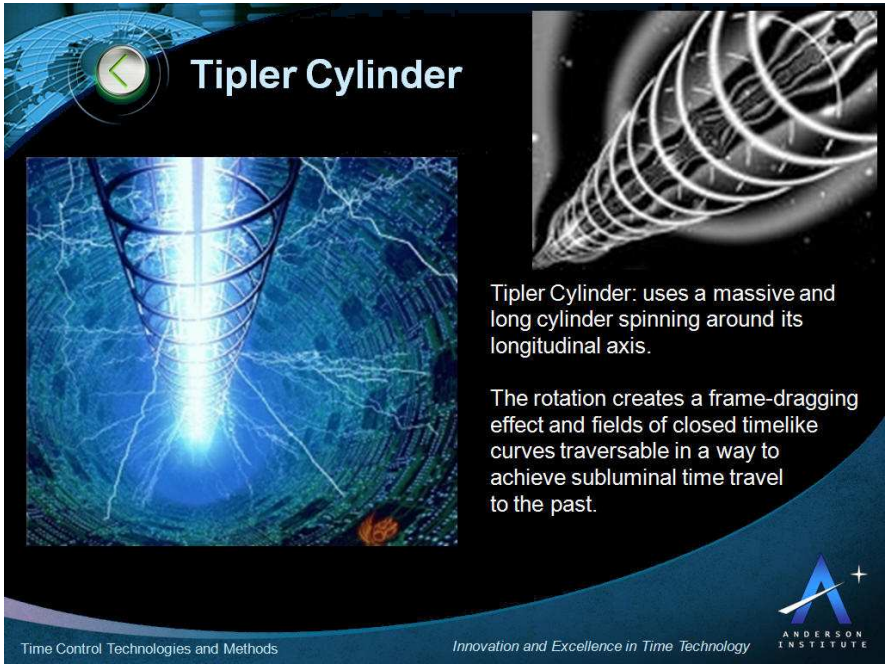
Two ways:

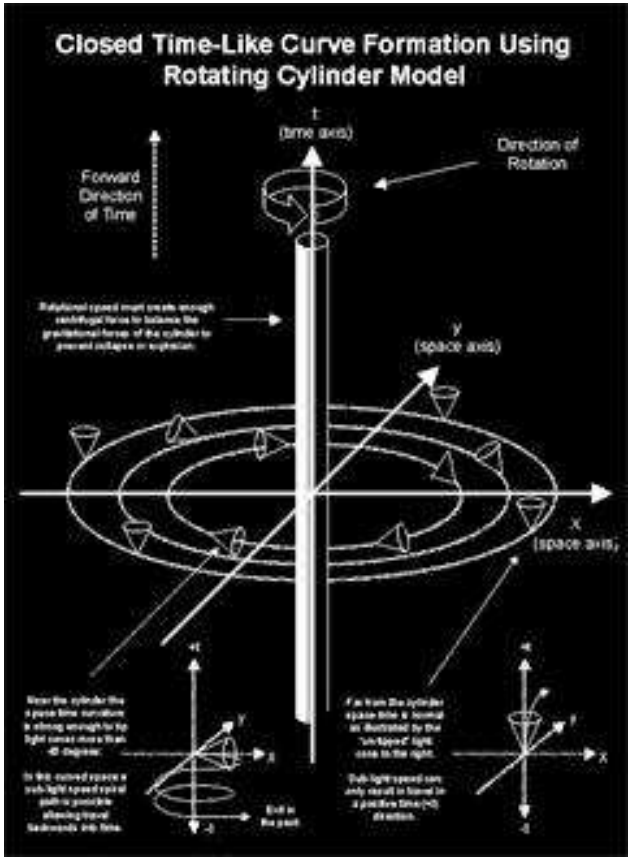
- We find a suitable, **existing** CTC and jump in!
- We create a **new** CTC: a "time machine"

We haven't yet found any existing CTCs, suitable or not, so let's go to the second option, which physicists have been busy with for decades…

Time Travel to the Past is Tricky—Machines

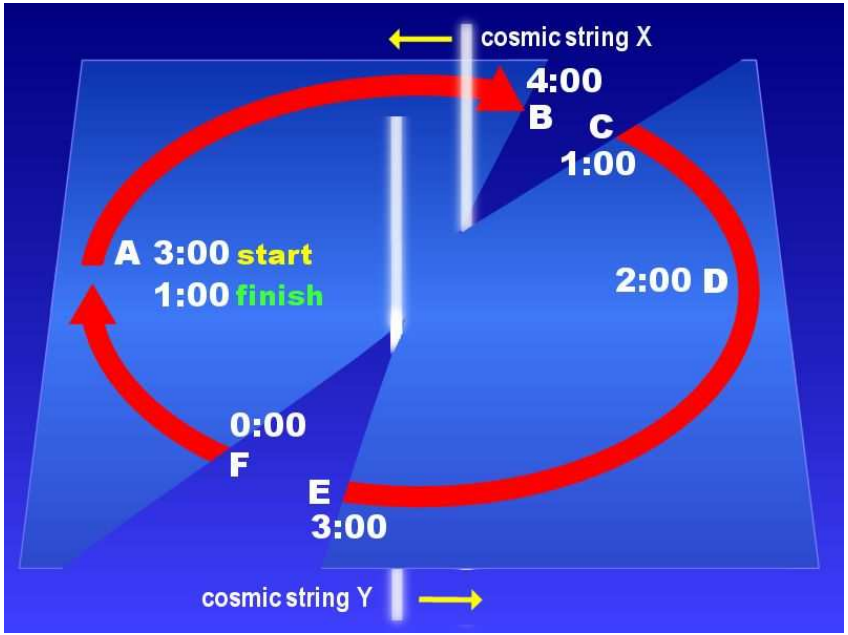
Example: **Tipler Cylinder Time Machine**





Time Travel to the Past is Tricky—Machines

Example: **The Gott Time Machine**



Both (Tipler & Gott) **would work**…

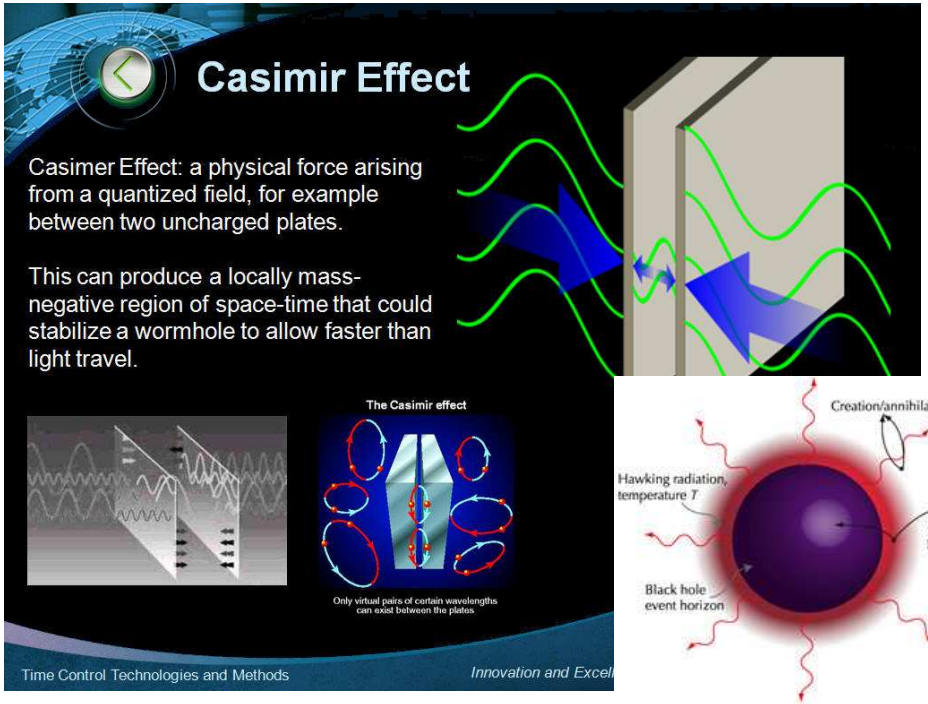
…except require **infinitely long** cylinder or strings

But engineers could only build **finitely** long structures. Stephen Hawking proved that CTCs cannot be created in a **finite** region of space without **exotic matter** (negative mass-energy), and the cylinder/strings are **not** exotic matter.

…so it would not work (& probably create a BH)

Time Travel to the Past is Tricky—Machines

Exotic Matter



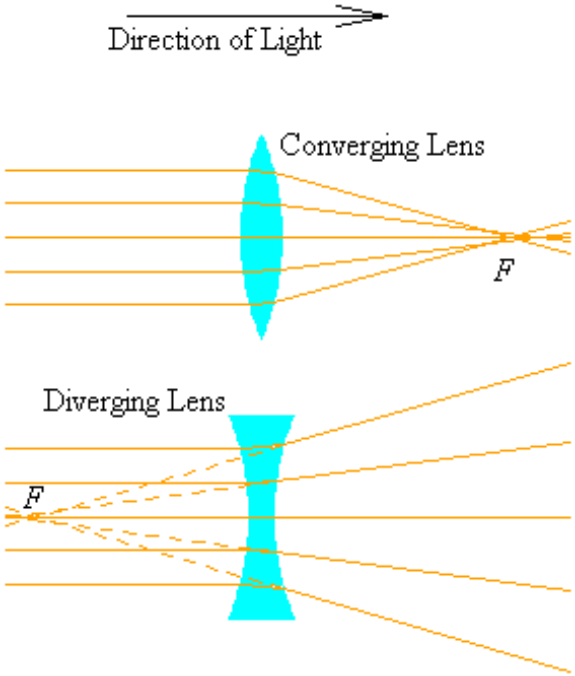
In a **classical** universe, it is believed that matter always has **positive** mass-energy.

If so, Hawking's theorem would appear to **rule out** the possibility of a time machine built in any **finite** region of space.

However, we live in a **quantum universe**, which *seems* to allow regions of **negative** mass-energy, e.g., the **Casimir effect** (discussed earlier). (Also, around BH…)

Time Travel to the Past is Tricky—Machines

Exotic Matter



What would exotic matter be good for?

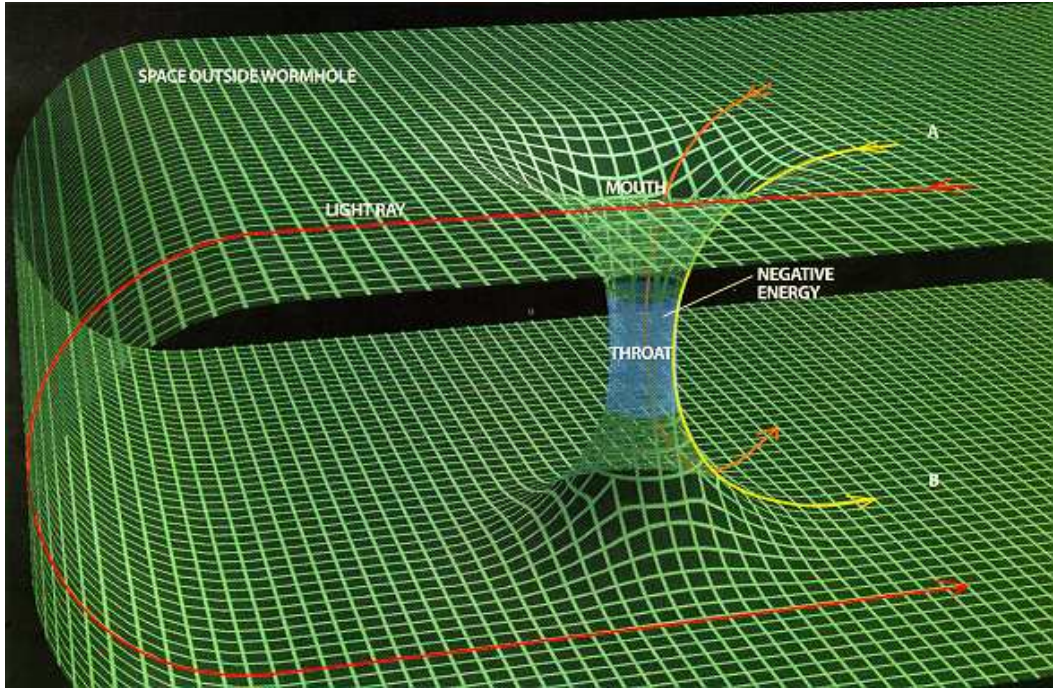
Analogy with lenses:

Positive mass-energy (like a positively curved lens) causes light to **converge**

Negative mass-energy (like a negatively curved lens) causes light to **diverge**

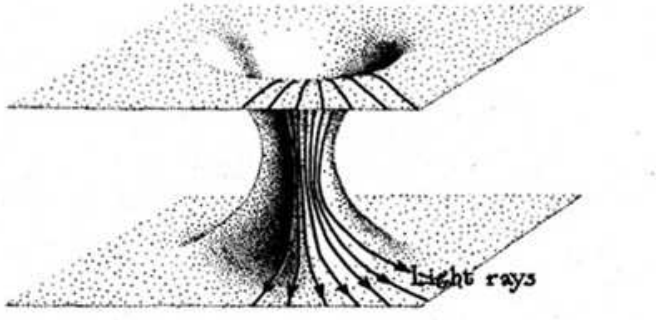
Time Travel to the Past is Tricky—Machines

Exotic Matter



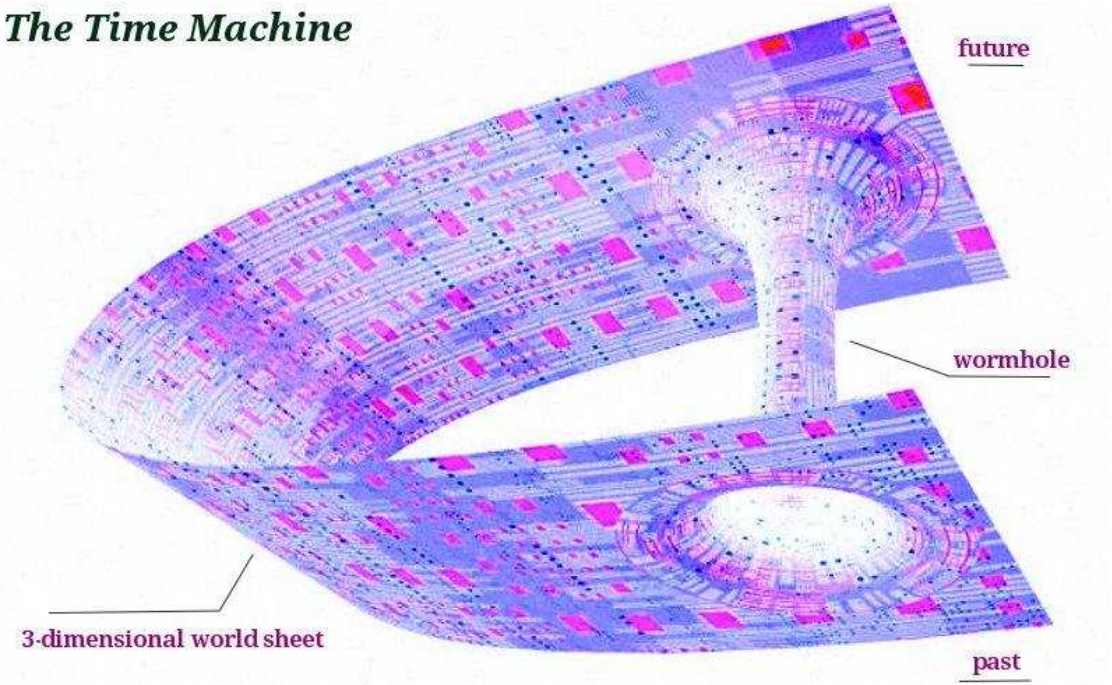
A classical wormhole is **unstable**.

The **diverging** effect of **negative** mass-energy could be used to **stabilize** (hold open) a wormhole…



Time Travel to the Past is Tricky—Machines

Exotic Matter

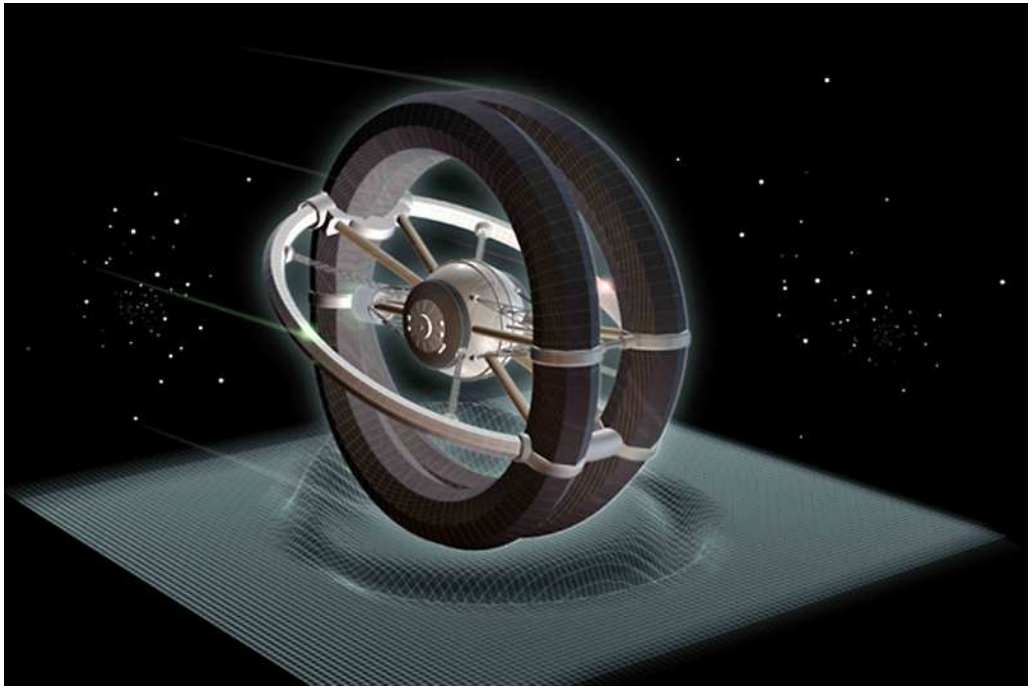


…then we could use MOTION (SR) or MASS (GR) to "move" one mouth of a wormhole *into the past* of the other mouth.

This creates a time machine to the past when traversing in one direction, and to the future in the other direction.

Time Travel to the Past is Tricky—Machines

Alcubierre Warp Drive



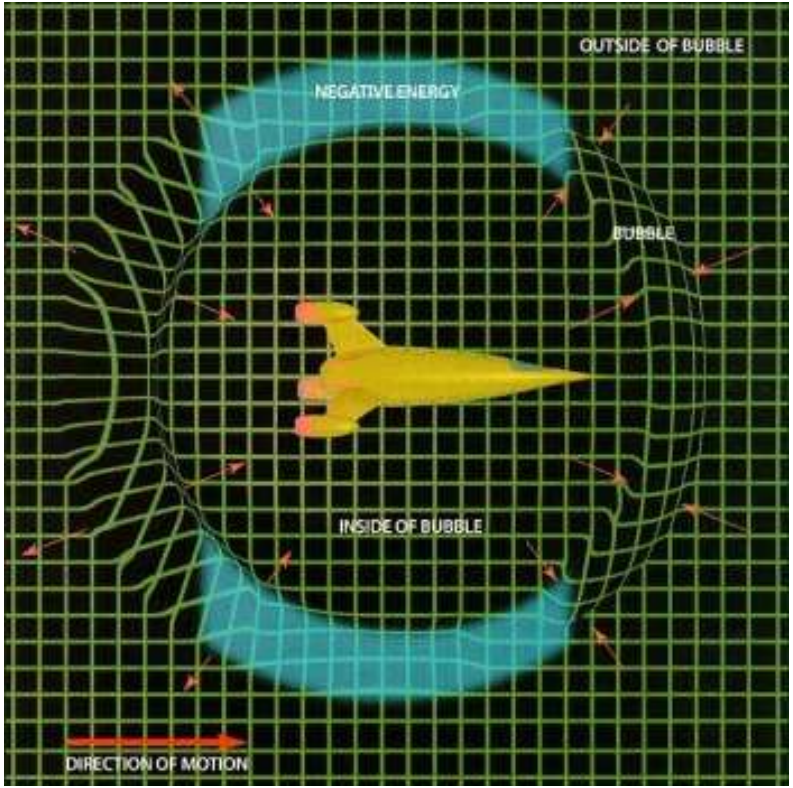
A form of **space travel** that is allowed by GR

Time Travel to the Past is Tricky—Machines

Alcubierre Warp Drive

Requires **exotic matter**:

Spaceship is surrounded by a bubble of **positive-** and **negative**-energy matter.



Time Travel to the Past is Tricky—Machines

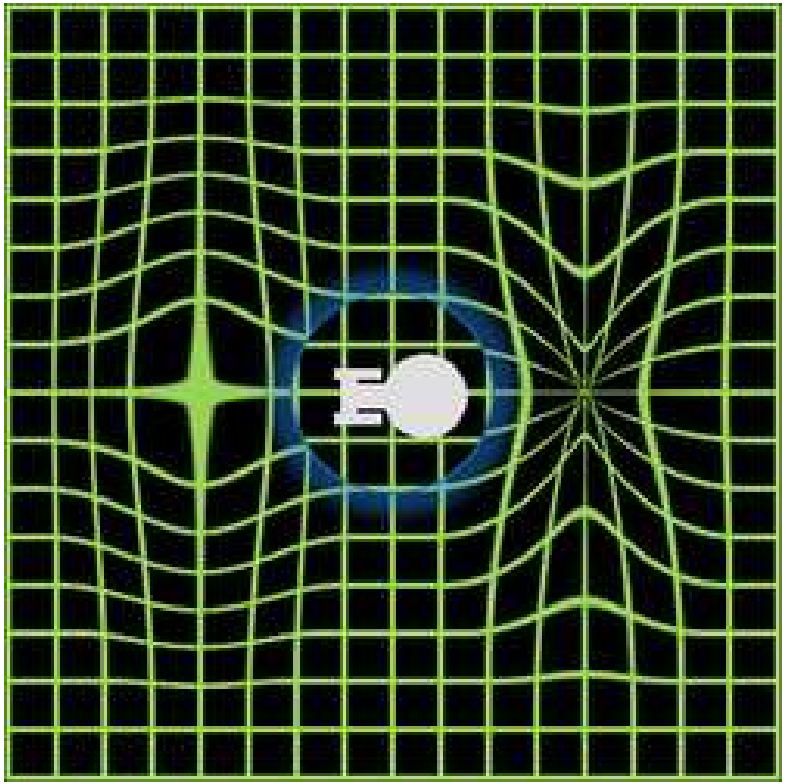
Alcubierre Warp Drive

Bubble of matter affects **contraction & expansion** of space:

Space in front **contracts**; space behind **expands**.

Bubble moves **faster than light**.

No problem for GR: Think about how rapidly space expanded during inflation!



Time Travel to the Past is Tricky—Machines

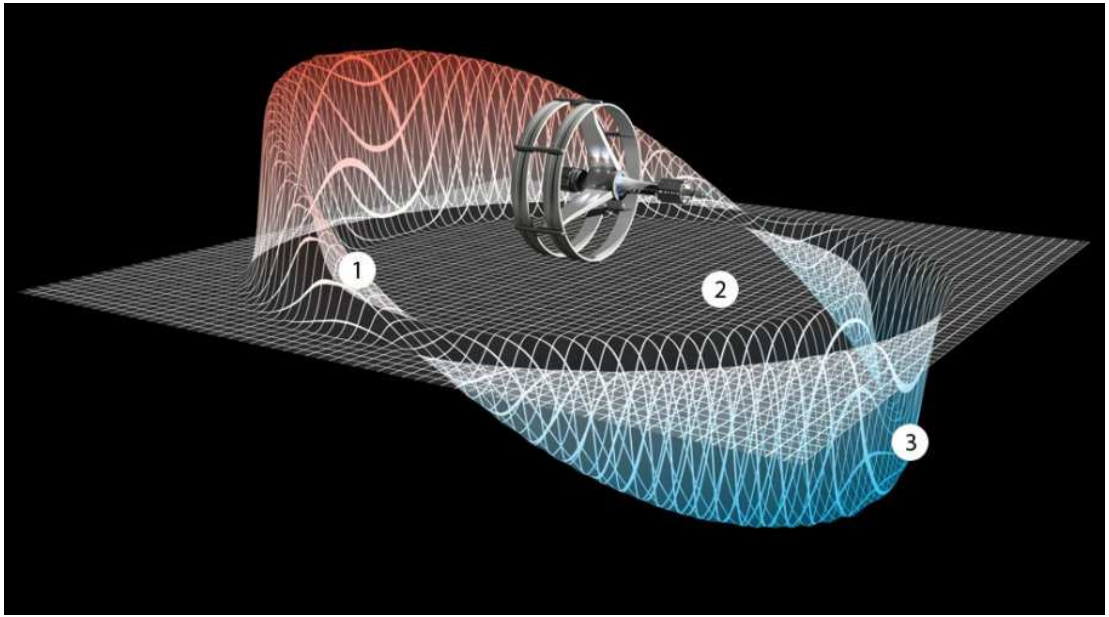
Alcubierre Warp Drive

No inertial effects inside the bubble!

"Frame dragging"

Exactly like Star Trek!

Because $v > c$, can also be seen as a time machine!



Time Travel to the Past is Tricky

Summary:

- The question of time travel is **not just for fun**. It is **useful**: it subjects our current understanding of the nature of reality to the **most severe though experiments**, which may show where our understanding **breaks down**, and thus clues to how it may be **improved**.

- **Classical** general relativity **allows time travel to the past**, but this results in **insurmountable paradoxes**. But the universe is **not classical**. Combining GR with **quantum ideas** *seems* to **remove the paradoxes**, and **may** even make building a time machine **possible** (at least in principle), although this **is far from certain**.

- Either way, trying to figure this out could teach us a lot about the **ultimate nature of reality**, and give us important clues towards a theory of quantum gravity, or **theory of everything**.

Time Travel to the Past is Tricky

Summary:

- But if it's really possible, **where are all the tourists from the future?**

…this is Stephen Hawking's version of the Fermi Paradox, and it raises similar big questions!