

Einstein's Bottomless Beanbag: Gravity and Black Holes

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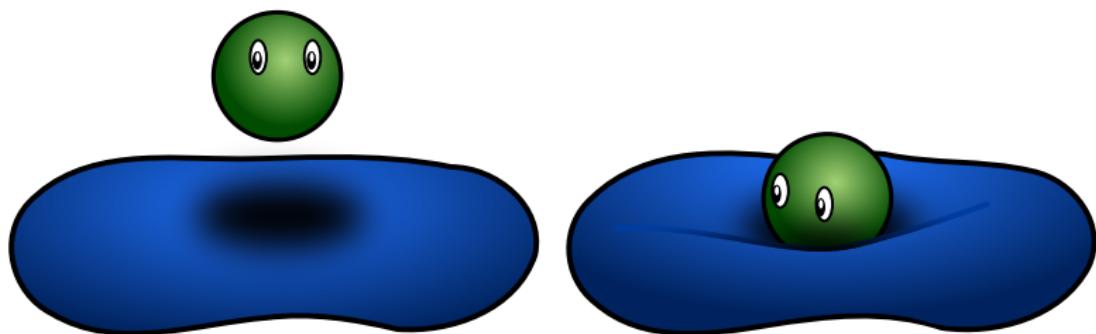


Science 101

Einstein's Beanbag

Bags which sag

- For hundreds of years, we used **Newton's theory of gravity**.
- In 1915, Albert Einstein invented a new theory of gravity called **general relativity**. It says the universe is like a beanbag!



- The beanbag is space itself. It is **flat** when nothing sits on it. But if we place mass on it, **the beanbag will sag**.
- John Wheeler: “Matter tells space how to curve.”
Or: **lumps tell the bag how to sag!**

Spreading out

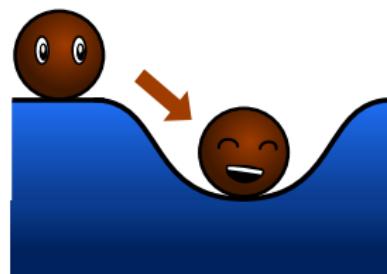
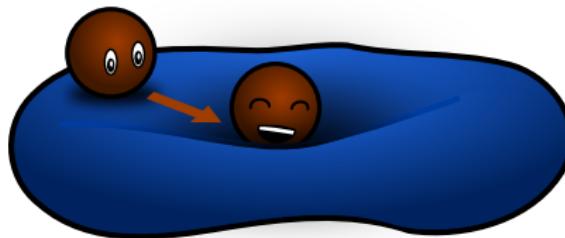
- The depth of a sag depends on how spread out the mass is.
- Ball and pancake have the same mass, but the pancake creates a shallow dip by spreading out its weight. Like snowshoeing!



- If an object gets denser without losing mass, it will create a deeper sag. This will be important later!

Lumps which flump

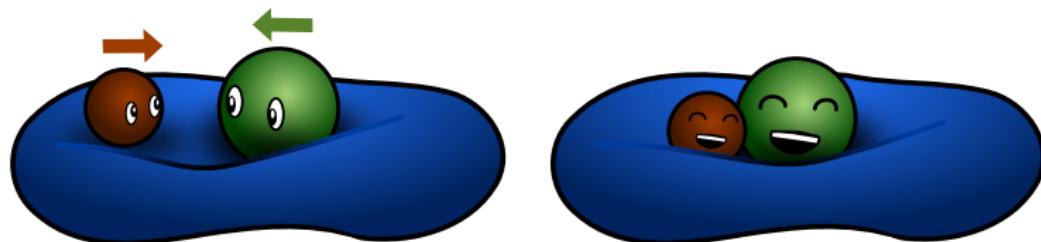
- A small mass comes along looking for somewhere to sit. The beanbag has dips and sags, but we **ignore** how they get there.
- The most comfortable seat is the **lowest!**



- The mass will roll until it reaches a **nearby dip**.
- Wheeler: “Space tells matter how to move.”
Or: **the bag shows a lump where to flump!**

Mutual attraction

- Newton's theory of gravity says that **masses are attracted**.
- We see something similar on the beanbag:
 - 1 Two nearby masses will **create their own dips**.
 - 2 Masses will **roll into nearby dips**.
 - 3 Therefore, **nearby masses roll into each other's dips!**

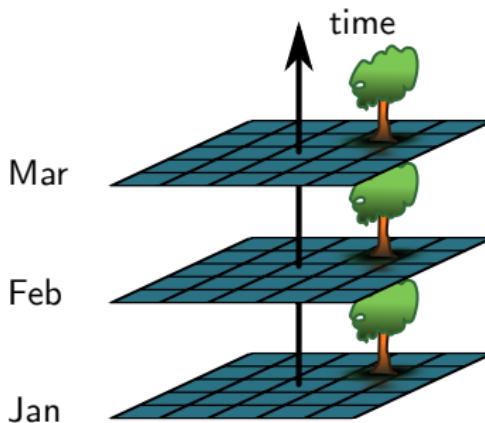


- This looks a lot like the **mutual attraction** Newton proposed.

Snapshots

An album of snapshots

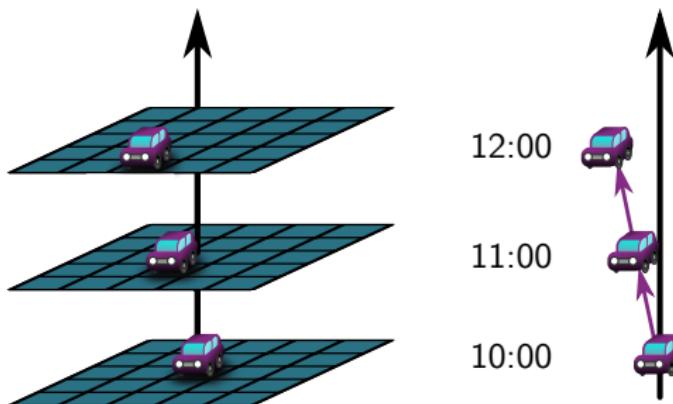
- Let's talk about **time**. We'll come back to the beanbag later.
- Imagine taking **snapshots** of space each month, and arranging them in a photo album. **We stack the photos vertically.**



- Photos are **taken from the same perspective**.
- Different pages in the album correspond to different times.
Going up takes you forward in time, and down goes backwards.

Moving around

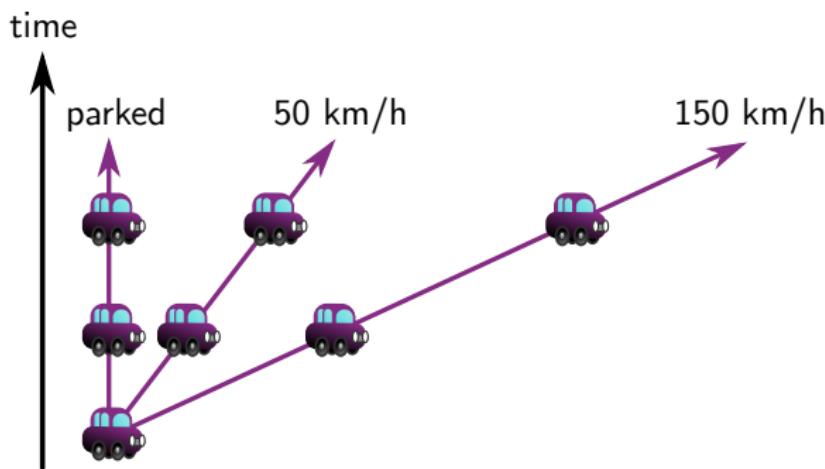
- Suppose we want to understand **how a particular object moves with time**. We can look at the photos from month to month.
- But photos will contain a lot of unnecessary details. **It's easier to ignore everything but the object itself!**



- We use **arrows** to show how the object travels from month to month. These arrows describe movement in space and time.

Need for speed

- The **tilt of an arrow** depends on the object's speed.
- A parked car stays in the same place, so **its arrow is vertical**. At 50 km/h **it tilts down**, and at 150 km/h it tilts even more.

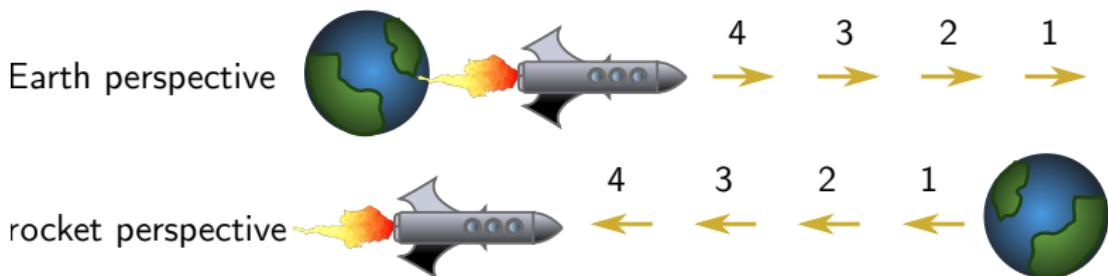


- The faster the object, the more it **tilts** away from the vertical.

Traffic cones

Racing light

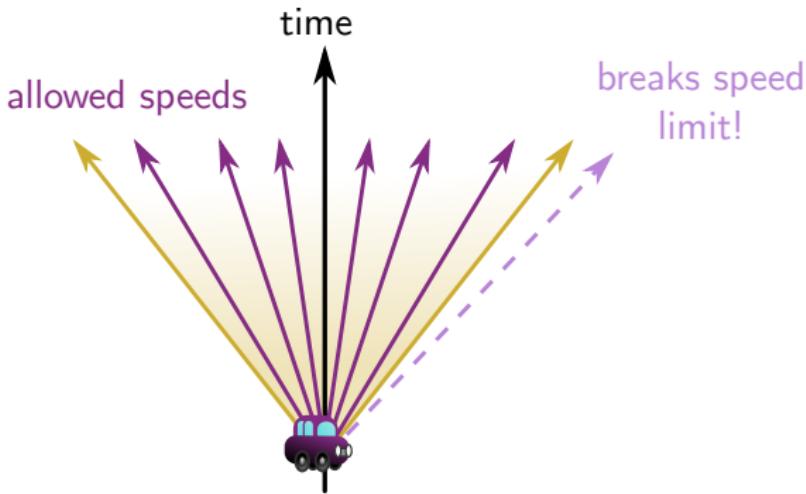
- Is there a speed limit? Or can we go as fast as we like?
- Suppose a spaceship can go **faster than the speed of light**. It will **catch up to light rays** which previously left Earth.



- Like a runner overtaking competitors, the rocket **encounters light rays in the opposite order** to which they left earth.
- From the rocket's perspective, **light rays arrive from in front**.

Universal speed limit

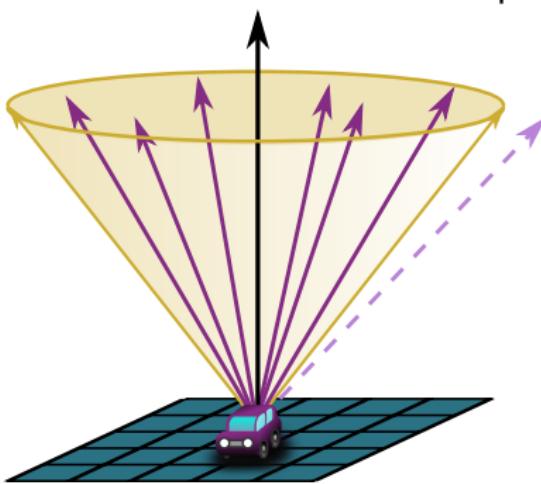
- Overall effect: earth appears **in front** and **backwards in time**.
- This is pretty weird! No one has ever seen it. So **the speed of light** is probably a **universal speed limit**.



- To obey the speed limit, **objects must stay between the yellow lines**. These lines are light rays moving in different directions.

The traffic cone

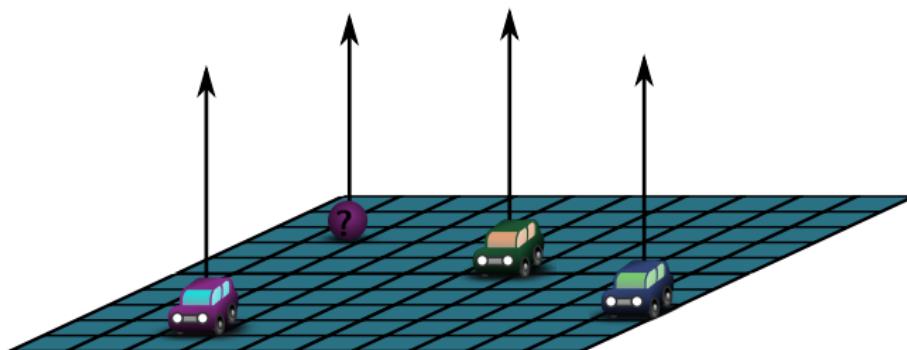
- If light can move in **two-dimensional space**, then all the light rays leaving a point **trace out a cone** in our photo album.



- This is called the **light cone**. The car must **stay within the cone** to obey the speed limit.
- It's **hard to visualise 3 dimensions + time**, so we stick to two!

Parking lots

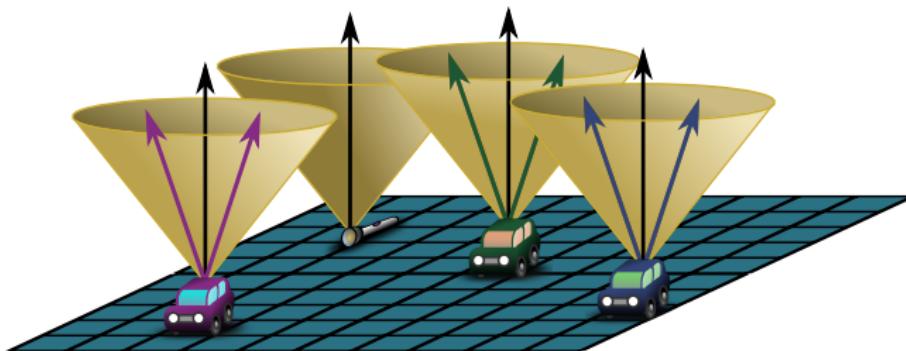
- We have been talking about a **single point** in space.
- But suppose we have make snapshots of a whole parking lot.
Every car has an arrow going vertically up!



- Even where there is no car, we can draw a vertical arrow to indicate **what a parked car would do**.

Light cones everywhere

- To leave the parking lot, a car needs to move.
- But remember the **universal speed limit**: each car must move within its light cone!

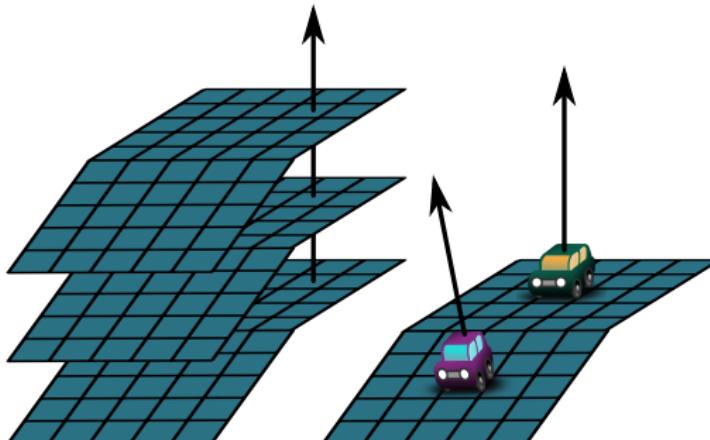


- We don't need cars to have light cones! A light cone is made by rays of light leaving a point, e.g. from a flashlight.

Tilted traffic

Beanbag snapshots

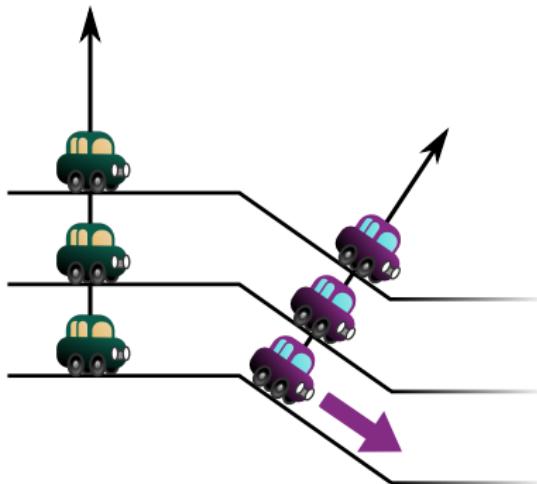
- Until now, we've considered traffic laws for **flat surfaces**. But on Einstein's beanbag, **the surface will sag due to mass**.
- To make photo albums, **we still stack photos vertically**. (We draw kinks rather than sags for simplicity.)



- But **if the surface tilts, the arrows tilt with it**. Imagine it is firmly attached to the top of the car, or the surface itself.

Parking on a hill

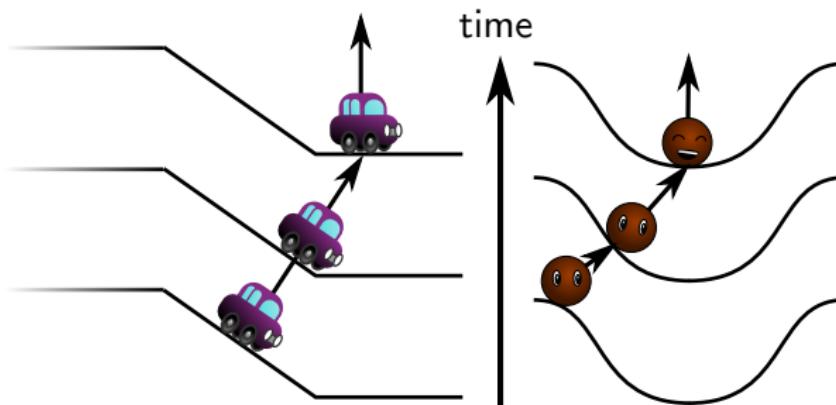
- When we stack photos, we extend tilted arrows to see how "parked" cars move. With a hill, they undergo relative motion!
- The green car's arrow points up, so it stays exactly where it is.



- But the purple car has a tilted arrow, so it seems to roll down. It's like parking on a real hill with the handbrake off!

Flumping revisited

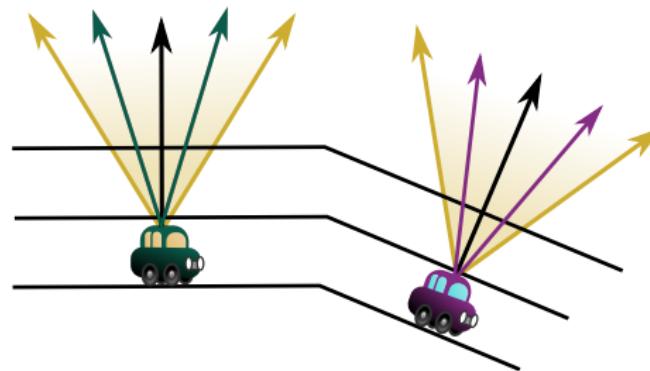
- Suppose the purple car keeps rolling to the bottom of the hill.
- At the bottom, **the arrow now points directly up**. The car wants to remain in the same place!



- But this is the **flumping** we discussed earlier! When a lump hits the bottom of a dip, it wants to stay. **Now we see why!**

Tilting cones

- Not only stationary arrows tip. The **whole light cone** is attached to the surface and tips over with it.
- This means **traffic laws change depending on the slope**.

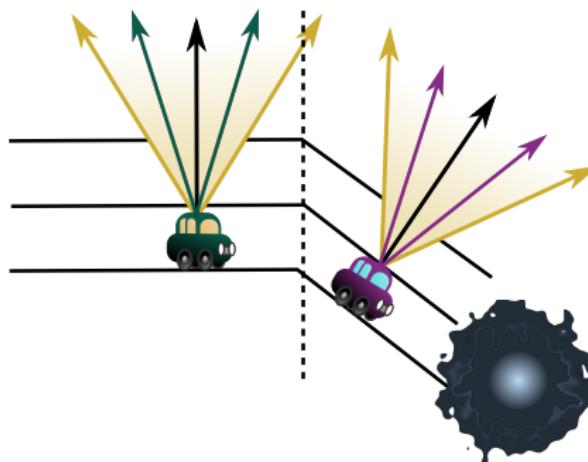


- From green's perspective, **purple's maximum speed up the hill is slower**. But purple can still get up the hill if it really tries!

Black holes

Trapping light

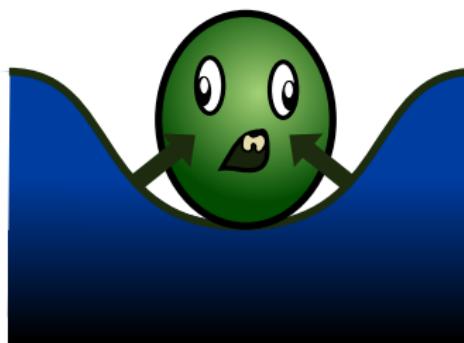
- That is, purple can't travel up the hill at all.
- This happens when purple's cone tips over so far that light cannot travel to the left. Even the light is trapped!



- Whenever light is trapped in a region, we call it a **black hole**. The dotted line is the **event horizon** or point of no return.

Making a black hole

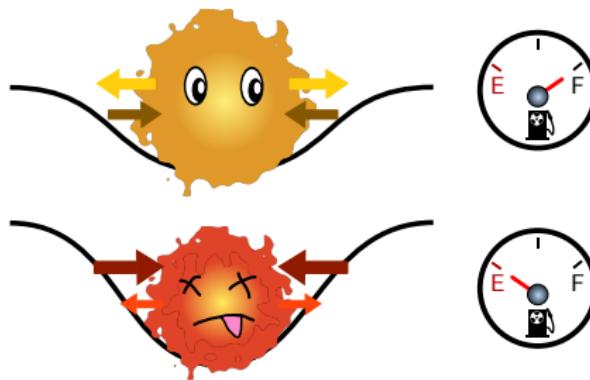
- How are black holes actually formed?
- The main mechanism is **self-gravity**. Heavy objects are not only attracted to other objects, **but also to themselves!**



- The sides of the object **get pushed towards the centre** where the sag is deepest and mass is concentrated.
- **Why don't I collapse to form a black hole?** The forces holding me together are much stronger than gravity!

Dying stars

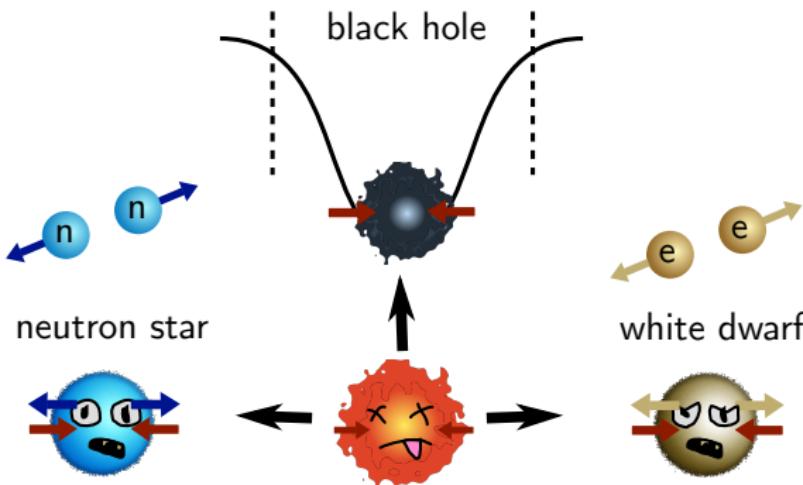
- A star is much heavier and self-gravity **much stronger**. But a healthy star **counters this with pressure from nuclear fusion**.



- But **when it runs out of nuclear fuel**, gravity begins to win!
- It will start to contract under its own weight. As it gets **denser**, the sag it makes in the beanbag **gets deeper**.

Stellar collapse

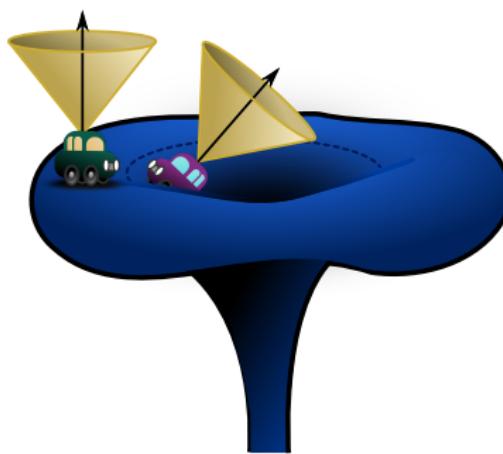
- Not every star forms a black hole. **What stops them collapsing** once they run out of fuel?
- They are converted into **repulsive** forms of matter!



- Smaller stars (like **our sun**) will become **white dwarfs made of electrons**, while larger stars get turned into **neutrons**.

The bottomless beanbag

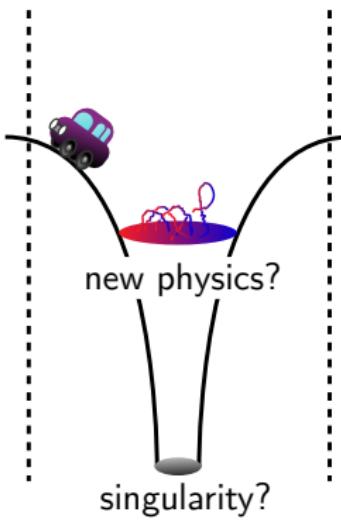
- Once it forms a black hole, the star keeps collapsing until it becomes **infinitely dense** with a **bottomless sag**.
- This is the **singularity**. Anything approaching is ripped apart!



- This is the endpoint of a black hole: a **violent singularity** surrounded by a **light-trapping region**.

Avoiding the singularity

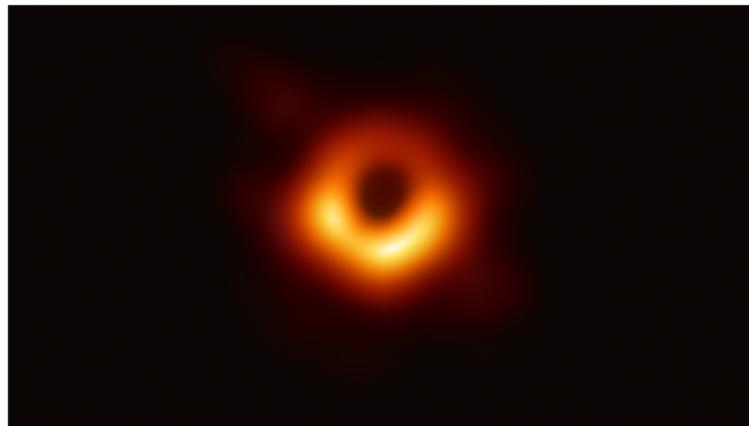
- Singularities seem unavoidable, but we're not sure they exist.
- New physical ideas (such as string theory) predict the singularity is smoothed out or capped off.



- The only way to check is to jump in! But you could never come back out to tell anyone.

Seeing is believing

- Although singularities are theoretical, **black holes are very real.** Below is a photo of the black hole at centre of M87.



- The black hole is the **shadow in the middle**. The orange ring is a **ball of gas** the black hole is eating.
- Theory and experiment **agree beautifully**. Nature is amazing!

Thanks for listening!