Black Holes:
Monsters of the Cosmos

The Science of Spacetime:

A Physicists Guide to the Galaxy

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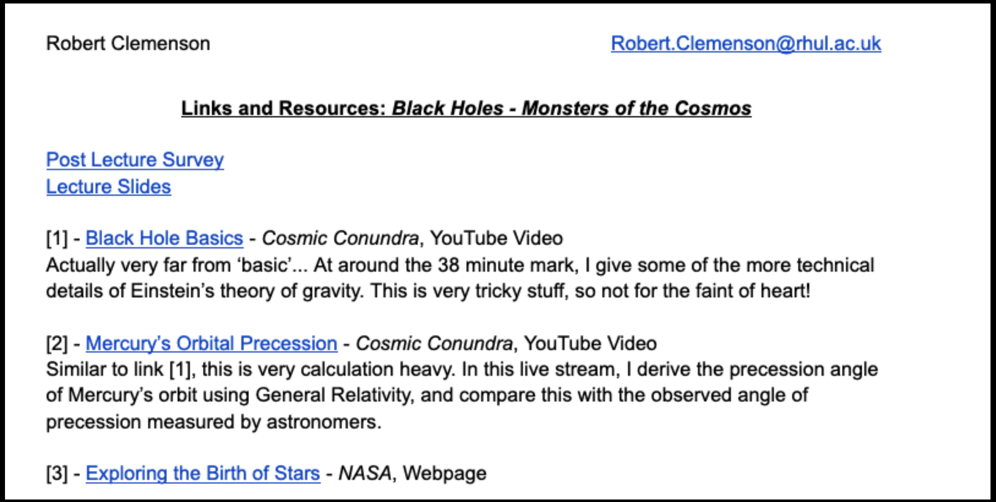
Southend Planetarium – 20.06.2026

Lecture Live Links (LLL)

Throughout the lecture, I will make a couple of references to previous talks, livestreams, and other online materials.

If you would like to check these out after the talk (or view recordings of previous lectures), please feel free to scan the QR code shown here.



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Links and Resources: *Black Holes - Monsters of the Cosmos*

Post Lecture Survey
Lecture Slides

[1] - Black Hole Basics - *Cosmic Conundra*, YouTube Video
Actually very far from 'basic'... At around the 38 minute mark, I give some of the more technical details of Einstein's theory of gravity. This is very tricky stuff, so not for the faint of heart!

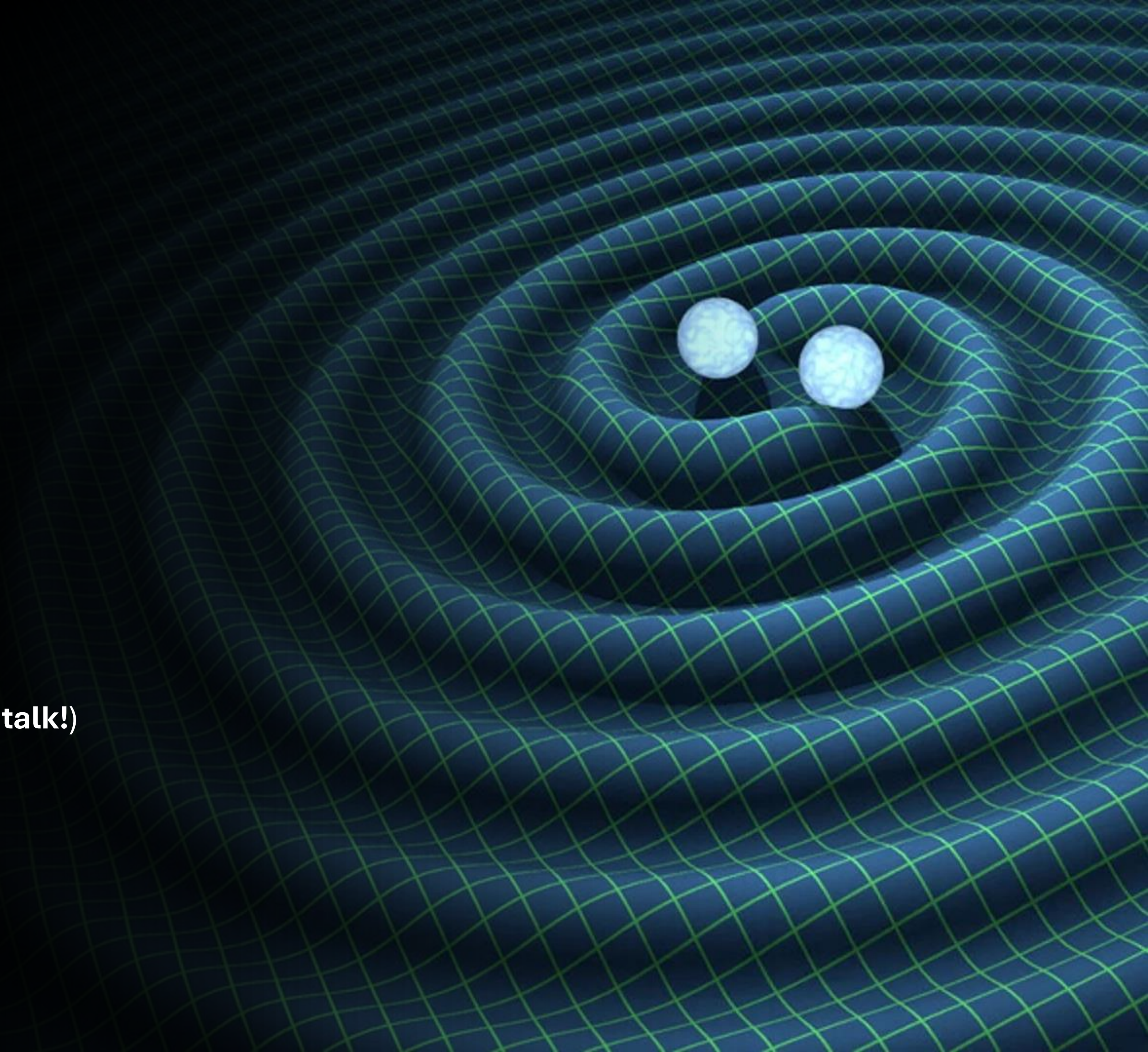
[2] - Mercury's Orbital Precession - *Cosmic Conundra*, YouTube Video
Similar to link [1], this is very calculation heavy. In this live stream, I derive the precession angle of Mercury's orbit using General Relativity, and compare this with the observed angle of precession measured by astronomers.

[3] - Exploring the Birth of Stars - *NASA*, Webpage

Scan the QR code above, or simply click the QR code in the PDF of the lecture slides.

Lecture Overview

- Gravity: From Newton to Einstein
- The Life of Stars: Birth to Death
- Black Holes in the Cosmos
- Black Holes as Time Machines
- Death by Black Hole
- Q&A (**Questions welcome throughout the talk!**)



Part I – Gravity: From Newton to Einstein

Gravity and *Levity*

In the ancient world, an objects desire to ‘fall’ or ‘float’ is described as an innate property of that object.

Aristotle tells us that Air and Fire posses levity (they want to move further from the ground), and Water and Earth possess gravity (they want to move closer to the ground).

Water has Gravity, Fire has Levity (so says Aristotle!).

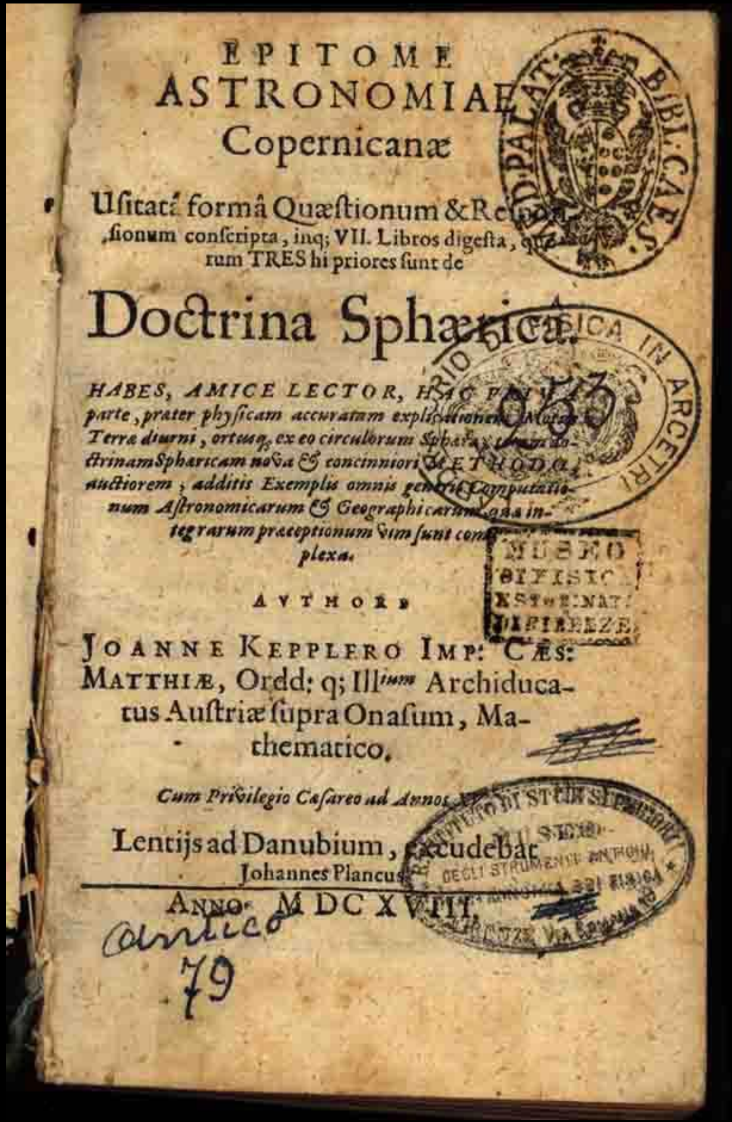
Aristotle, 330 BC.

Kepler's Laws of Planetary Motion

Kepler published the third of his three laws of planetary motion in 1619.

These three laws describe the motions of the planets, and build upon Copernicus' 1543 Heliocentric Model.

These laws come directly from observation, as opposed to theory. Kepler used the observations of Tycho Brahe (a 16th century Danish astronomer).


EPITOME
ASTRONOMIAE
Copernicanæ

Doctrina Sphærica.

AVTHORE
JOANNE KEPPLERO IMP: CÆS:
MATTHIÆ, Ordd: q; Illm̄ Archiducatus Austriæ supra Onasum, Mathematico.

Lentijs ad Danubium, excudebat Johannes Plancus
ANNO MDCXVIII.

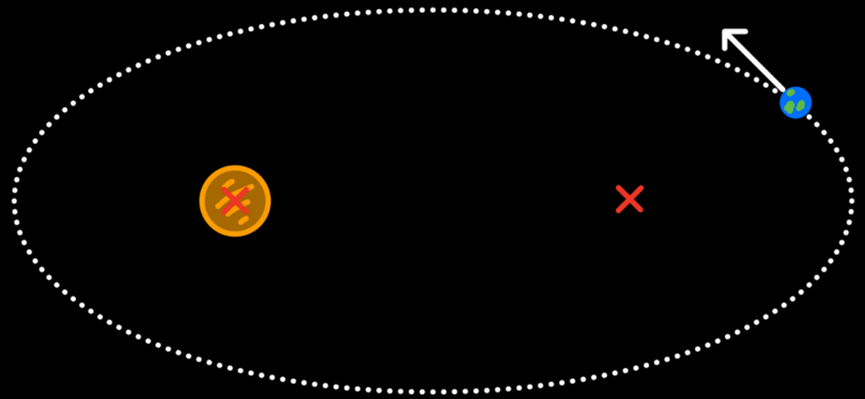
Epitome Astronomiae Copernicanae, where Kepler first published his three laws together.


Johannes Kepler, 1610.

Kepler’s Laws of Planetary Motion

Kepler’s First Law

Planets move along elliptical paths, with the sun centered at one focus.



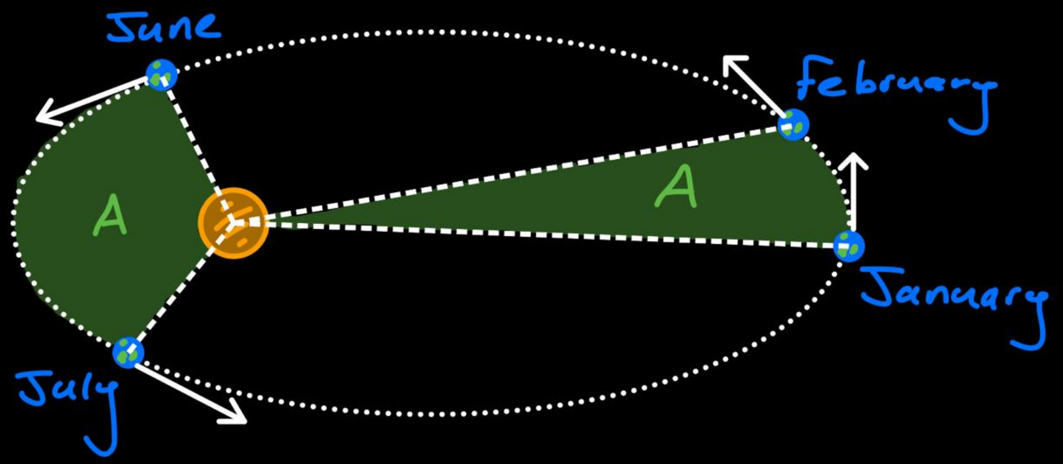
An ellipse is a kind of squashed circle, with geometric properties that have been studied by mathematicians since the 4th century BC.

Kepler's Laws of Planetary Motion

Kepler's Second Law

The area *swept out* by a planet in orbit is unchanged, given a fixed duration.

The origin of this law, is the conservation of angular momentum. As a planet moves closer to its star, it speeds up.



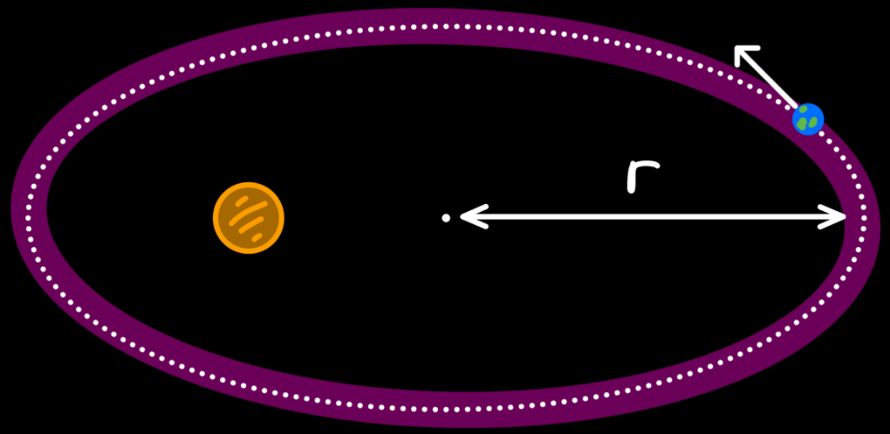
Kepler's Laws of Planetary Motion

Kepler's Third Law

The square of the orbital period is directly proportional to the cube of the orbital radius cubed.

This law was the key for Newton to work out his equation of gravity.

Technically an ellipse doesn't have a radius… The length shown is in fact called the *semi-major axis* of the ellipse.



$$T^2 \propto r^3$$

Newton's Law of Universal Gravitation

In 1687, Isaac Newtons published his breakthrough text, *Philosophiæ Naturalis Principia Mathematica*.

The Principia outlines his law of Universal Gravitation.

Universal – Gravity affects all objects with mass. Not only the heavenly bodies.

Newton's apple tree in the grounds of Woolsthorpe Manor in Lincolnshire.

Isaac Newton, 1702.

Newton's Law of Universal Gravitation

At a more technical level, it was the insights from Kepler's laws that allowed Newton to figure out his equation of gravity.

In order for the planets to move in elliptical paths, the force of gravity between two masses must go like the inverse square of the distance between the masses.

To come to this realization, Isaac Newtons had to invent the core mathematical field of *calculus* (**all before turning 23!**).

$$F = \frac{GMm}{d^2}$$

$$G = 6.67 \times 10^{-11} = 0.0000000000667$$

Newton's Law of Universal Gravitation

The Law instructs us on how to calculate the force of gravitational attraction between two masses.

The 'big G' constant at the front bears Newton's name (Newton's Gravitational Constant).

Note the small size of this constant, surprising the strength of the gravitational force.

The relative weakness of gravity, compared to the other fundamental forces remains an open problem in particle physics.

$$F = \frac{GMm}{d^2}$$

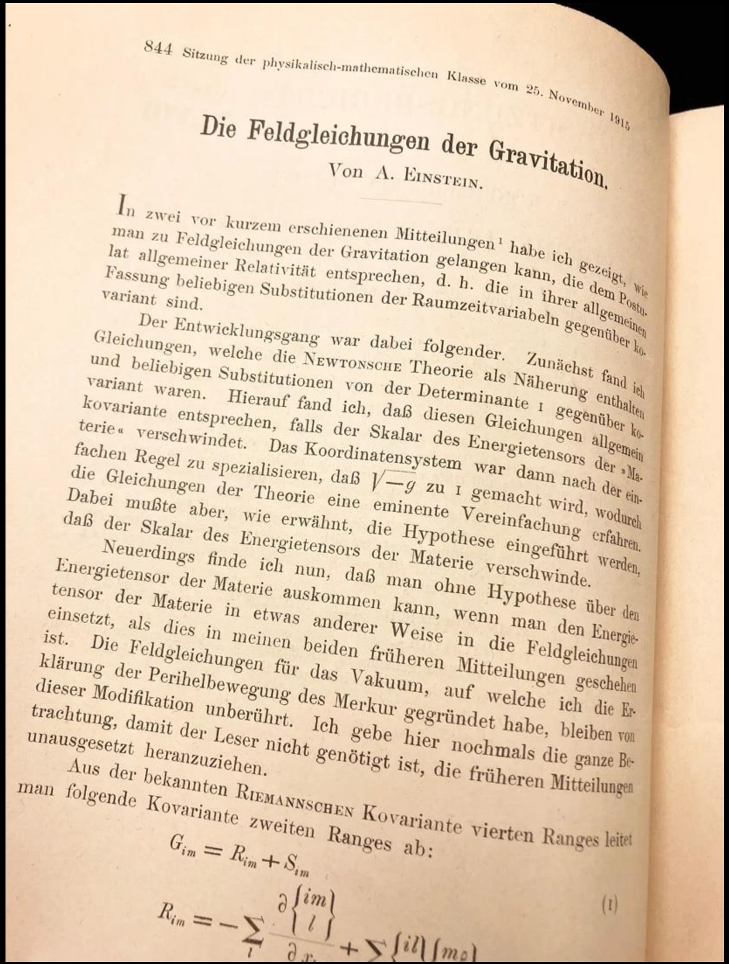
$$G = 6.67 \times 10^{-11} = 0.0000000000667$$

General Relativity

In November 1915, Albert Einstein publishes four papers, on four successive Thursdays.

The fourth of these papers, *The Field Equations of Gravitation*, sets out Einstein's new mathematical description of gravity.

The details of Einstein's theory are highly complex, but we will discuss some of the core ideas.



844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten und beliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der »Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu 1 gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren. Dabei mußte aber, wie erwähnt, die Hypothese eingeführt werden, daß der Skalar des Energietensors der Materie verschwinde.

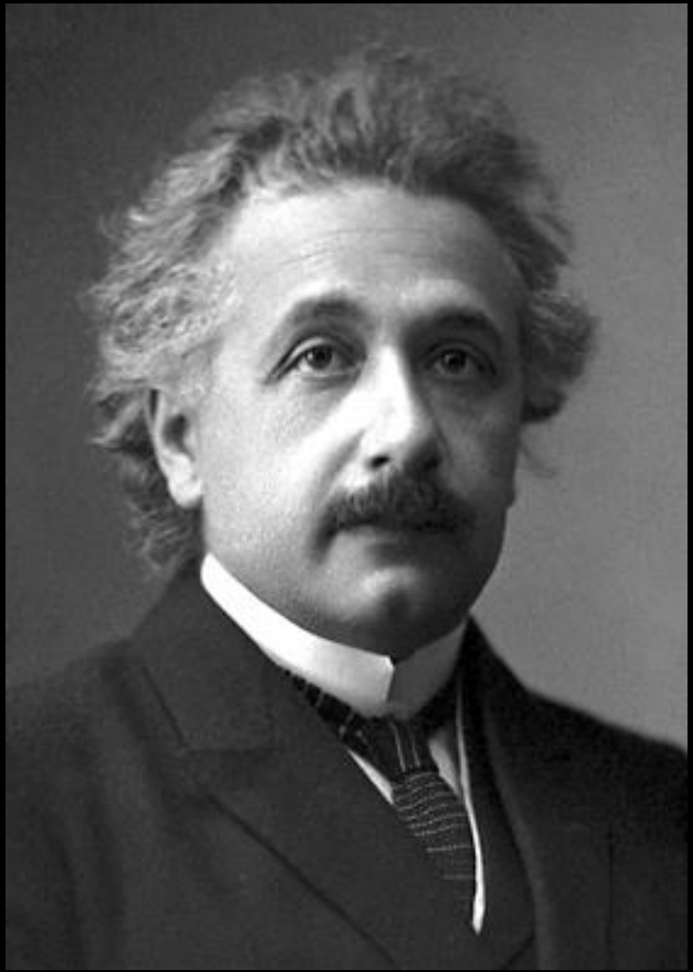
Neuerdings finde ich nun, daß man ohne Hypothese über den Energietensor der Materie auskommen kann, wenn man den Energietensor der Materie in etwas anderer Weise in die Feldgleichungen einsetzt, als dies in meinen beiden früheren Mitteilungen geschehen ist. Die Feldgleichungen für das Vakuum, auf welche ich die Erklärung der Perihelbewegung des Merkur gegründet habe, bleiben von dieser Modifikation unberührt. Ich gebe hier nochmals die ganze Betrachtung, damit der Leser nicht genötigt ist, die früheren Mitteilungen unausgesetzt heranzuziehen.

Aus der bekannten Riemannschen Kovariante vierten Ranges leitet man folgende Kovariante zweiten Ranges ab:

$$G_{im} = R_{im} + S_{im}$$

$$R_{im} = -\sum_l \frac{\partial \begin{Bmatrix} im \\ l \end{Bmatrix}}{\partial x_l} + \ldots \quad (1)$$

The Field Equations of Gravitation, published Nov 25th 1915.



Albert Einstein, 1921.

General Relativity

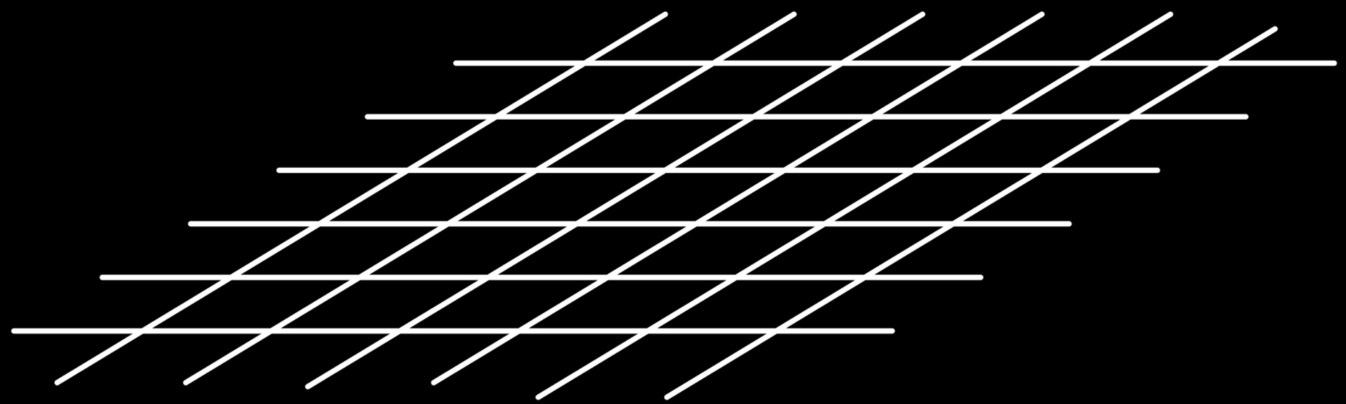
LLL [1]

Einstein's Equivalence Principle:

Gravity is indistinguishable from acceleration.

This is the insight that allows Einstein to conclude that gravity is a *geometric phenomena*.

Einstein's earlier work on the theory of special relativity (1905) puts space and time into a single united framework, *four-dimensional space time*.



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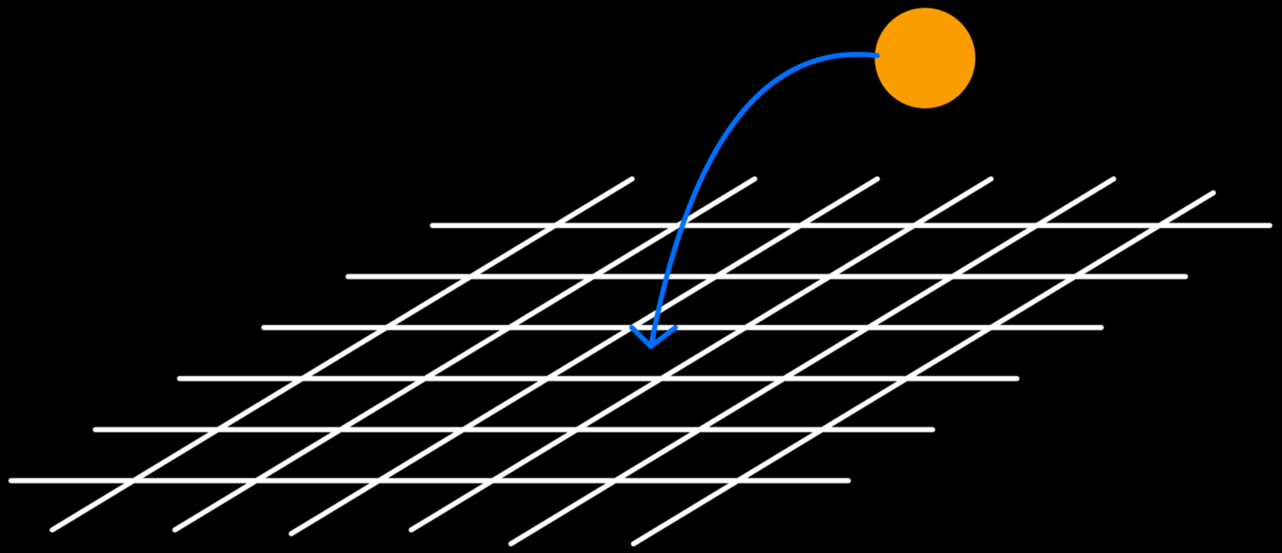
Space and time are more than just the stage on which physics happens, they are players.



Let's add a piece of matter into this flat region of space.

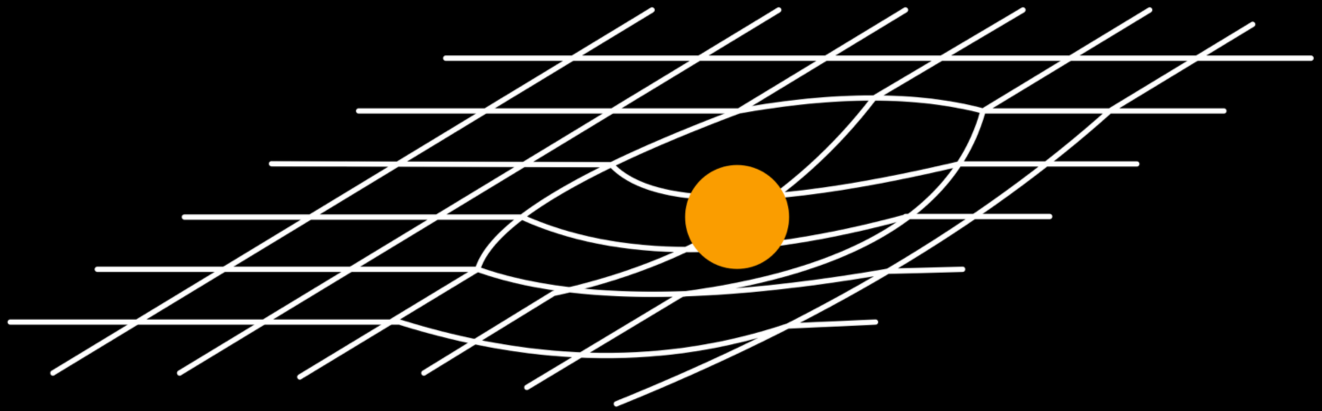
General Relativity

The presence of matter, causes space-time to curves.

The curvature of space-time cases matter to experience the illusion of a gravitational force.

'Spacetime tells matter how to move; matter tells spacetime how to curve.' – John Wheeler

Space-time is more than just the stage on which physics happens, they are players too.



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time Curvature

Speed of Light

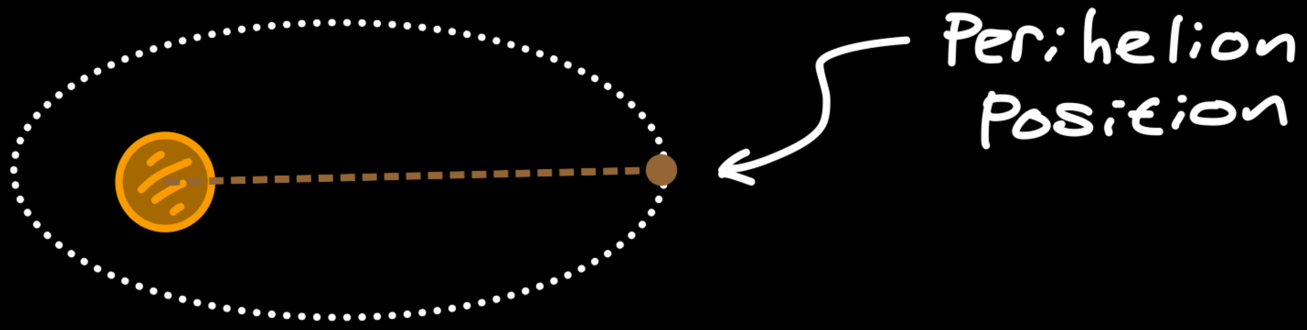
Matter

General Relativity

How do we know Einstein was right?

The abnormal precession of Mercury's perihelion was a longstanding problem in celestial mechanics (first pointed out in 1859 by Urbain La Verrier).

When physicists used Newton's Equation of Gravity to calculate the shape of Mercury's orbit, the calculated rate of advance of Mercury's perihelion is very far from the rate observed by astronomers.



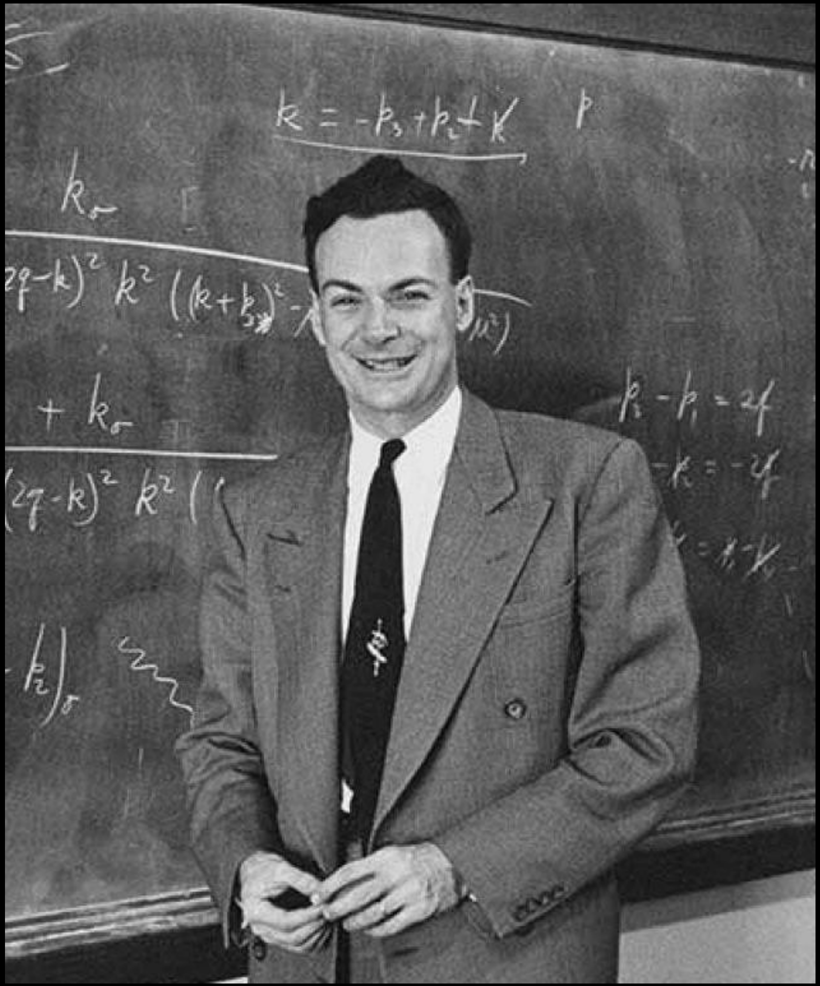
Perihelion – Point of greatest distance from the sun, in a planets elliptical orbit.

Feynman's Golden Rule

"In general, we look for a new law by the following process: First we guess it; then we compute the consequences of the guess to see what would be implied if this law that we guessed is right; then we compare the result of the computation to nature, with experiment or experience, compare it directly with observation, to see if it works.

If it disagrees with experiment, it is wrong. In that simple statement is the key to science. It does not make any difference how beautiful your guess is, it does not make any difference how smart you are, who made the guess, or what his name is — ***if it disagrees with experiment, it is wrong****."*

Richard Feynman



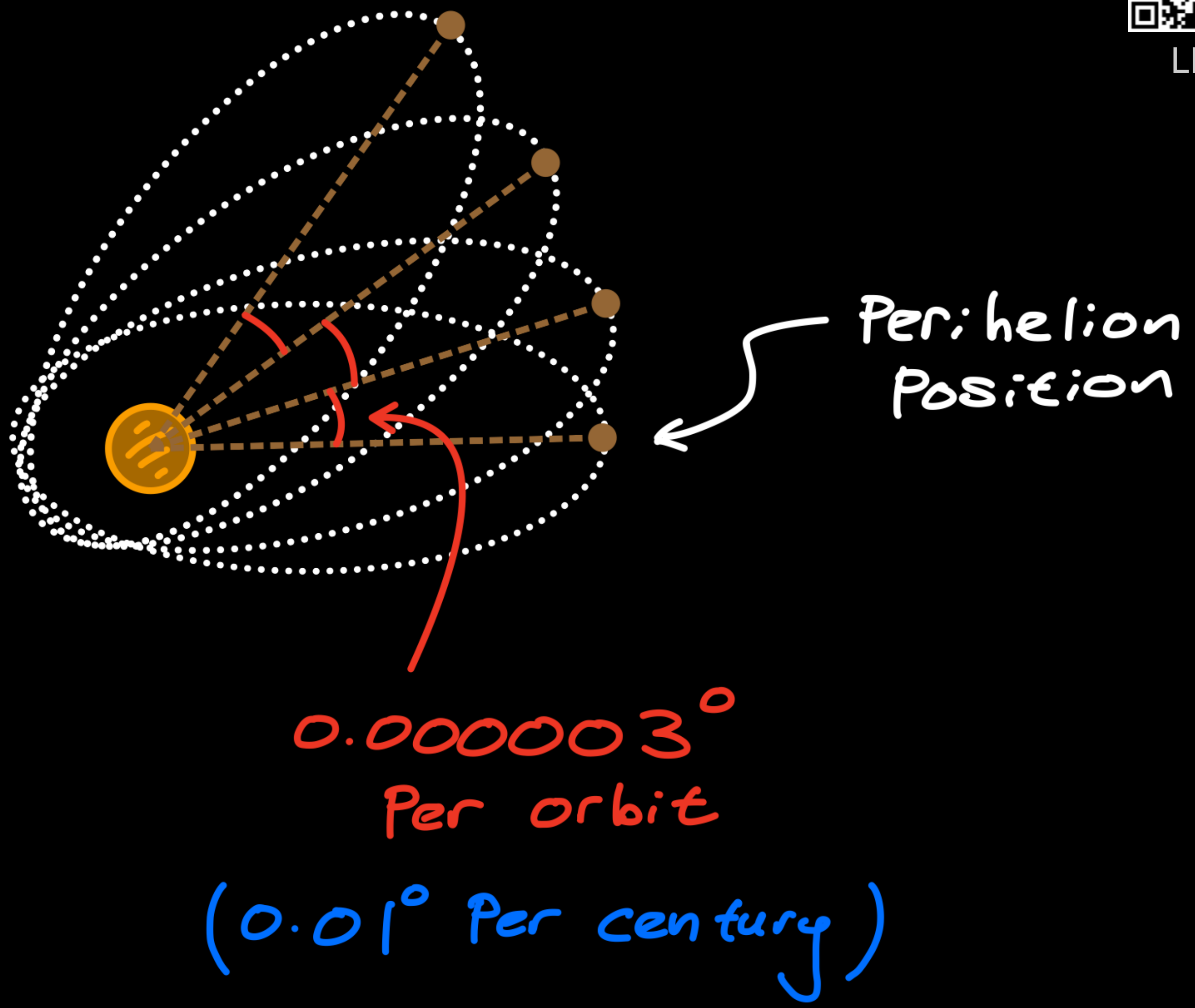
General Relativity

LLL [2]

How do we know Einstein was right?

When we use Einstein's Equation of Gravity to perform the same calculation, the answer matches the observation made by astronomers to a very high degree of accuracy.

This is one feather in General Relativity's cap!



Newton vs Einstein

"If it disagrees with experiment, it is wrong." *– R.P. Feynman*

However… **Wrongness is a spectrum!**

"Absolute truth" is a challenging concept, and not one we grapple with in the sciences.

Science deals with models:

A description of a physical system that allows us to understand *some* aspects of the phenomena and make testable predictions. This does not mean that the model has to work in *all circumstances*.

Newton vs Einstein. The battle for the laws of gravity

Note: This is an AI generated image.

Newton vs Einstein

Einstein vs Newton is a good example.

Newton's theory of gravity allows us to (mostly) explain the orbits of planets in our solar system, and the dynamics of our galaxy. Newton's theory allowed us to get to the moon.

Einstein's theory of gravity (General Relativity) predicts the existence of black holes, and solves subtle problems related to the orbit of the planets that Newton's theory cannot explain.

Newton vs Einstein. The battle for the laws of gravity

Note: This is an AI generated image.

Newton's theory works for (relatively) small masses. Einstein's theory picks up where Newton's left off, and tells us more about larger masses and subtle (harder to observe) effects.

Part II – The Life of Stars: Birth to Death

Like a Phoenix, from the ashes…

Stars are born from the clouds of gas and dust left behind from the explosive deaths of earlier stars.

We call these stellar graveyards / nurseries, ***Nebulae***.

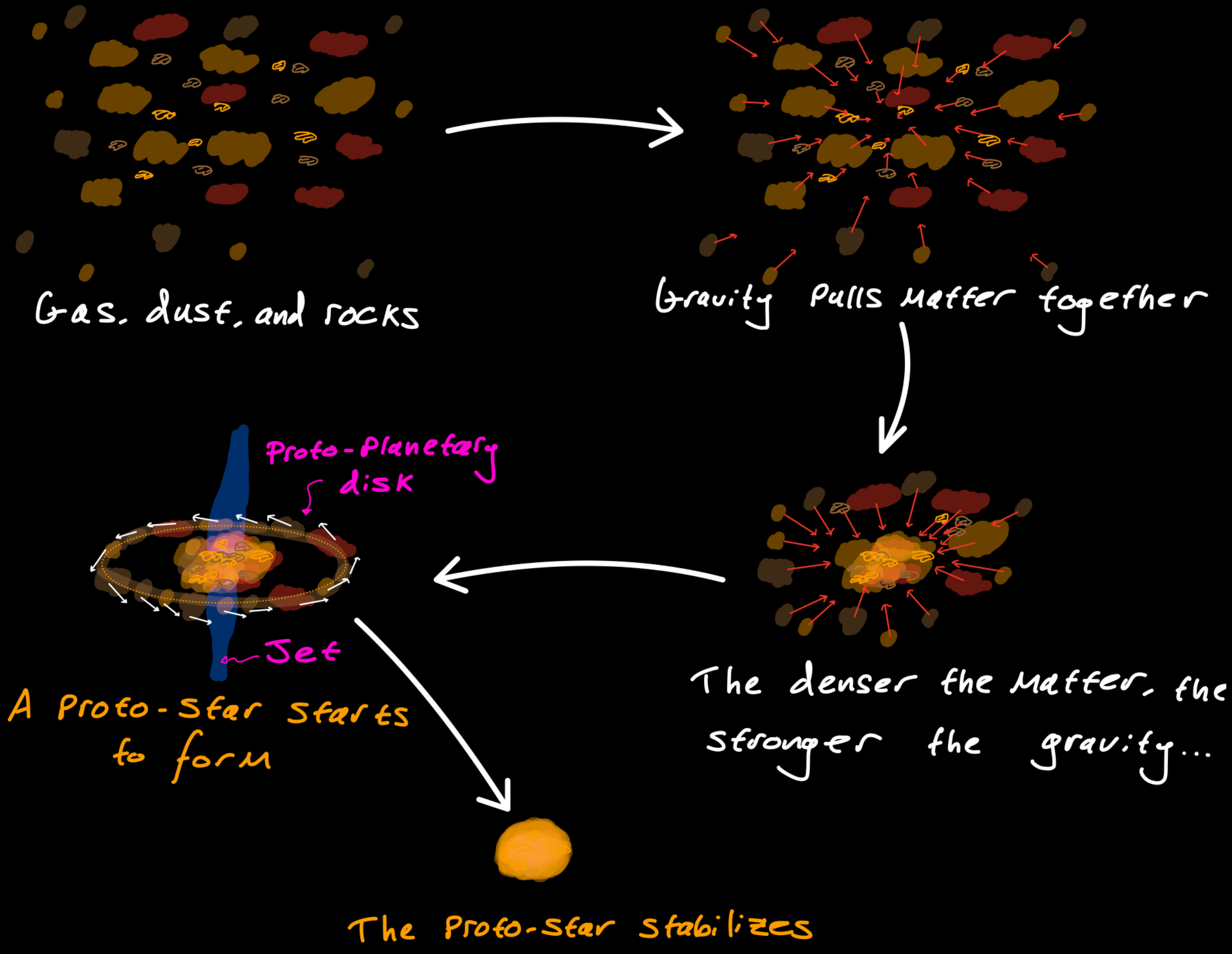
Pictured in the backdrop is the part of the Carina Nebula. A vast and varied amalgam of stellar nurseries, supergiant stars, and globular structures. 230 lightyears across and nearly 8500 lightyears from the Earth

Birth of a Star

Newton's law of gravity teaches us that *more mass* means *more gravity*.

Local excess density leads to gravitational collapse of the surrounding matter.

A star is born!

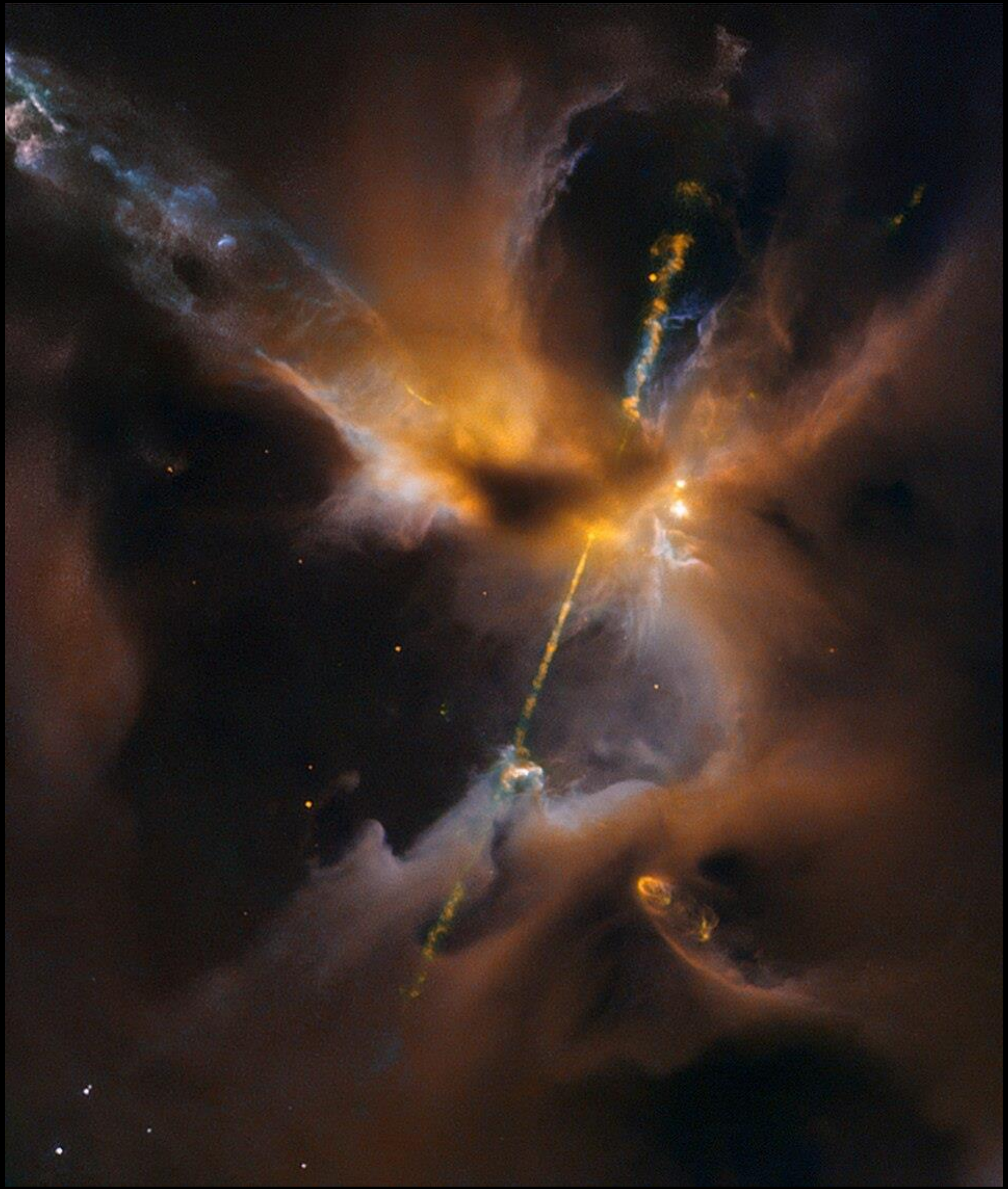


Birth of a Star

We can witness the birth of stars in nebulae, by searching for *Herbig-Haro objects*.

These regions of brighter nebulae are formed when jets of plasma fire out of the poles of a proto-star, exciting the gases within the nebular causing them to glow more brightly.

LLL [3]



HH 24, in the Orion B Molecular Cloud

Main Sequence Stars

LLL [4]

Around 90% of all stars in the Universe are in the *Main Sequence* phase of their life cycle.

This is the phase in which stars spend the majority of their burning lifetime.

The Sun

[Taken from Southend by Dawid Glawdzin (@dawidgphotography)]

Main Sequence Stars

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More of Dawid's Astrophotography

The Sun

[Taken from Southend by Dawid Glawdzin (@dawidgphotography)]

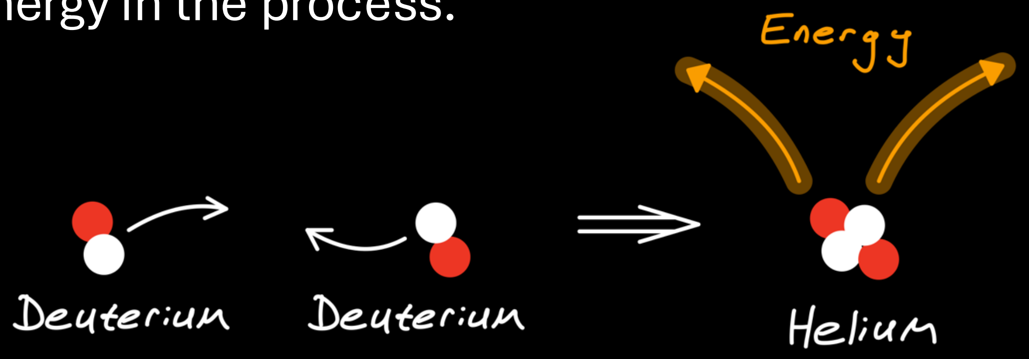
LLL [4]

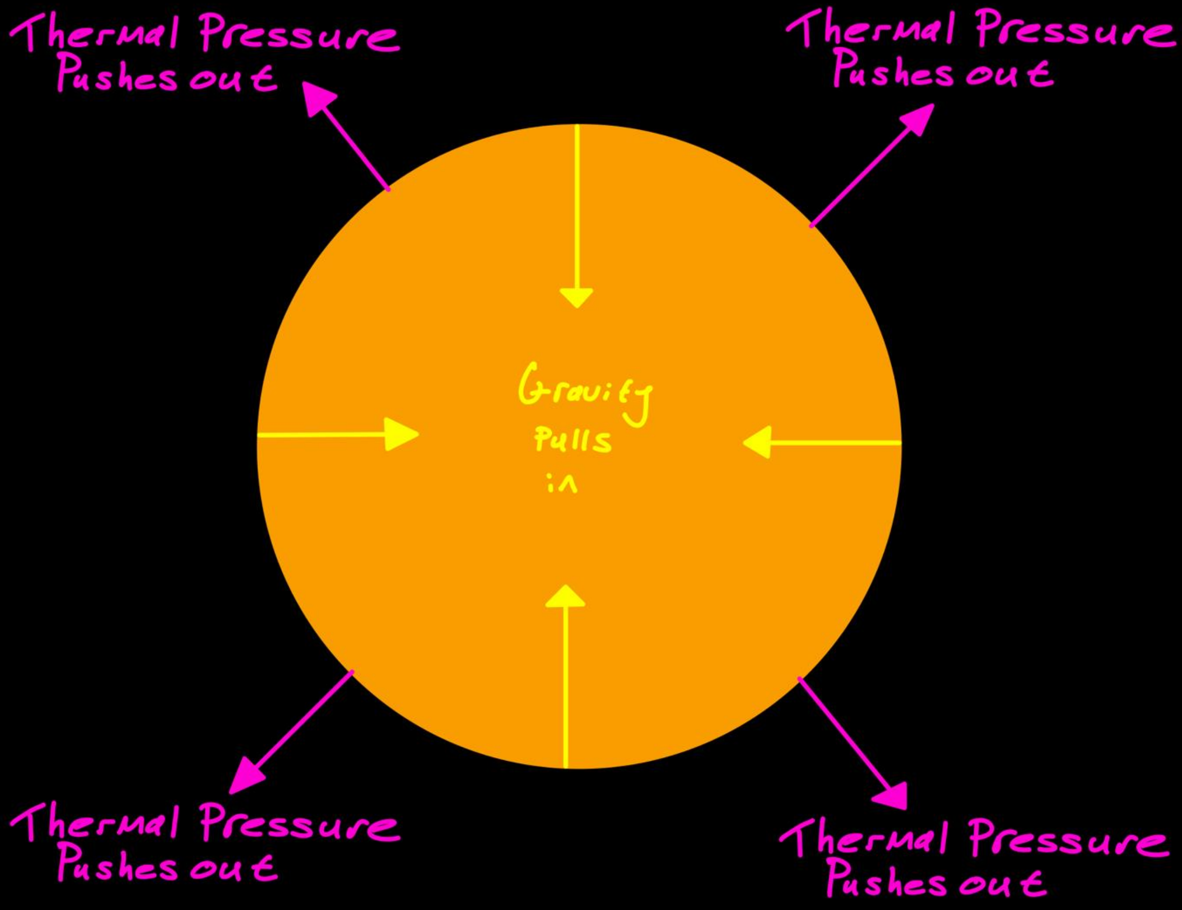
Main Sequence Stars

LLL [5]

The Main Sequence is characterized by stability, with forces of *gravity* (pulling inwards) and forces of *thermal pressure* (pushing outwards) in balance.

The origin of this *thermal pressure* is *Nuclear Fusion* in the core of the Star; squeezing Hydrogen isotopes into Helium, releasing huge amounts of energy in the process.





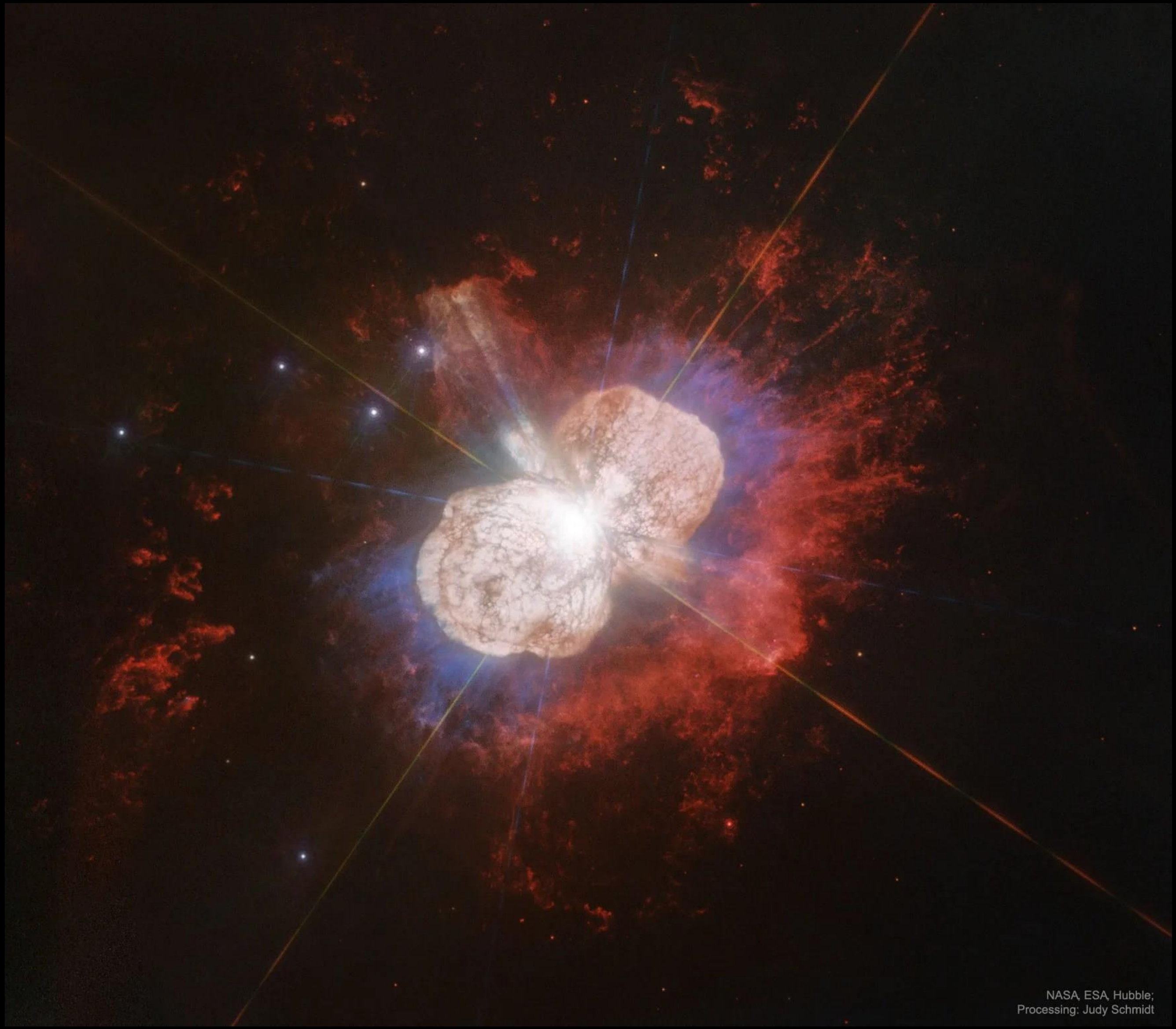
LLL [6]

Supergiant Stars

If a star is large enough (typically at least 8 times the mass of the sun), it will at some point in its life cycle form some kind of *Supergiant Star*.

Astronomers believe that the Eta Carinae system contains two supergiant stars in a binary orbit.

The largest of the two, Eta Carinae A, is a Blue Supergiant.

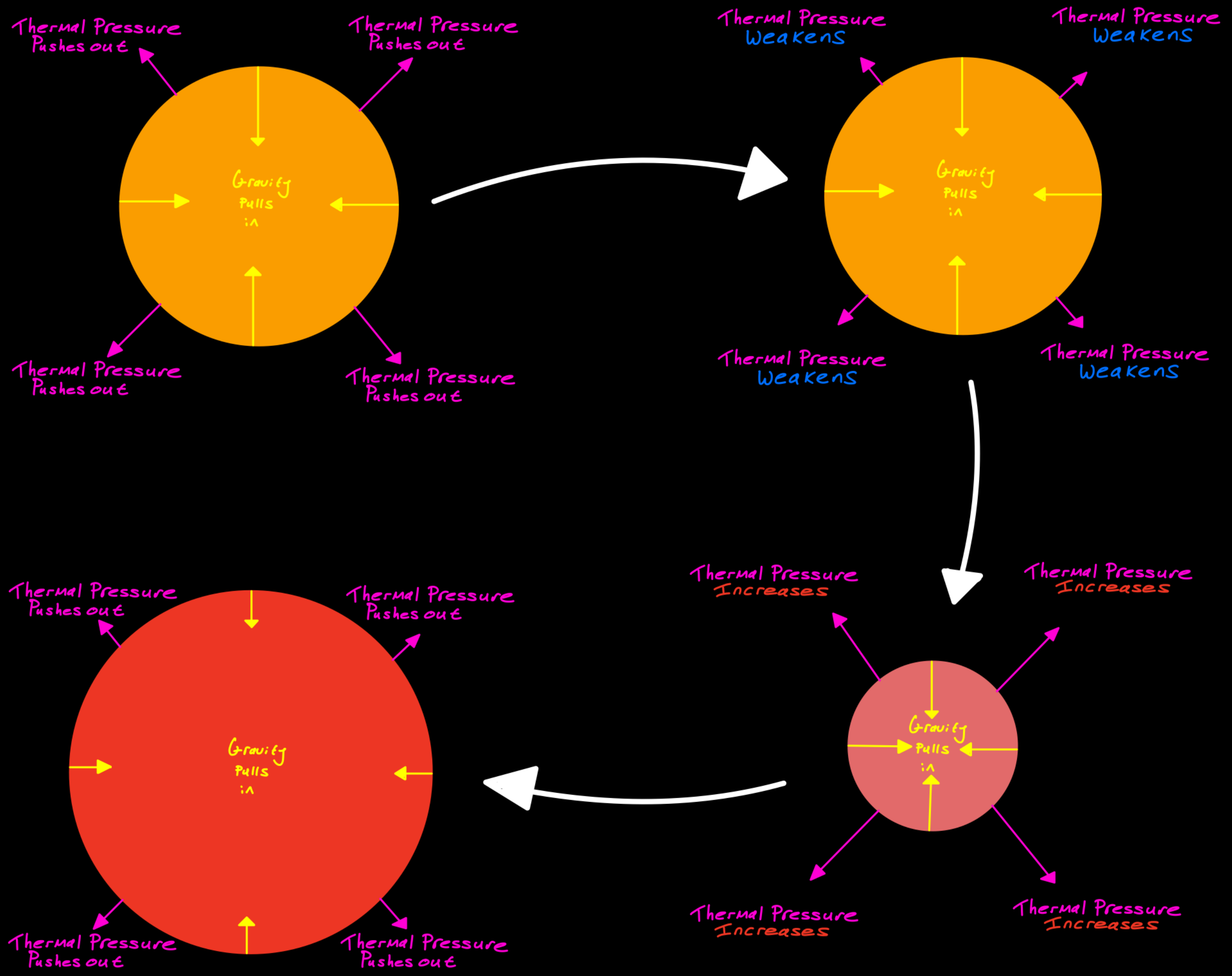


The Eta Carinae System, buried in the Homunculus Nebula. This system is comprised of two stars: one at least 30 times the mass of the sun, and another at least 100 times the mass of the sun.

Supergiant Stars

When one force gets the upper hand, changes occur within the star.

1. Hydrogen in the core runs out.
2. Fusion slows down.
3. The core cools, and gravity takes advantage.
4. The core contracts
5. Core temperature increases.
6. Outer layers absorb heat from the core and expand into a Supergiant.

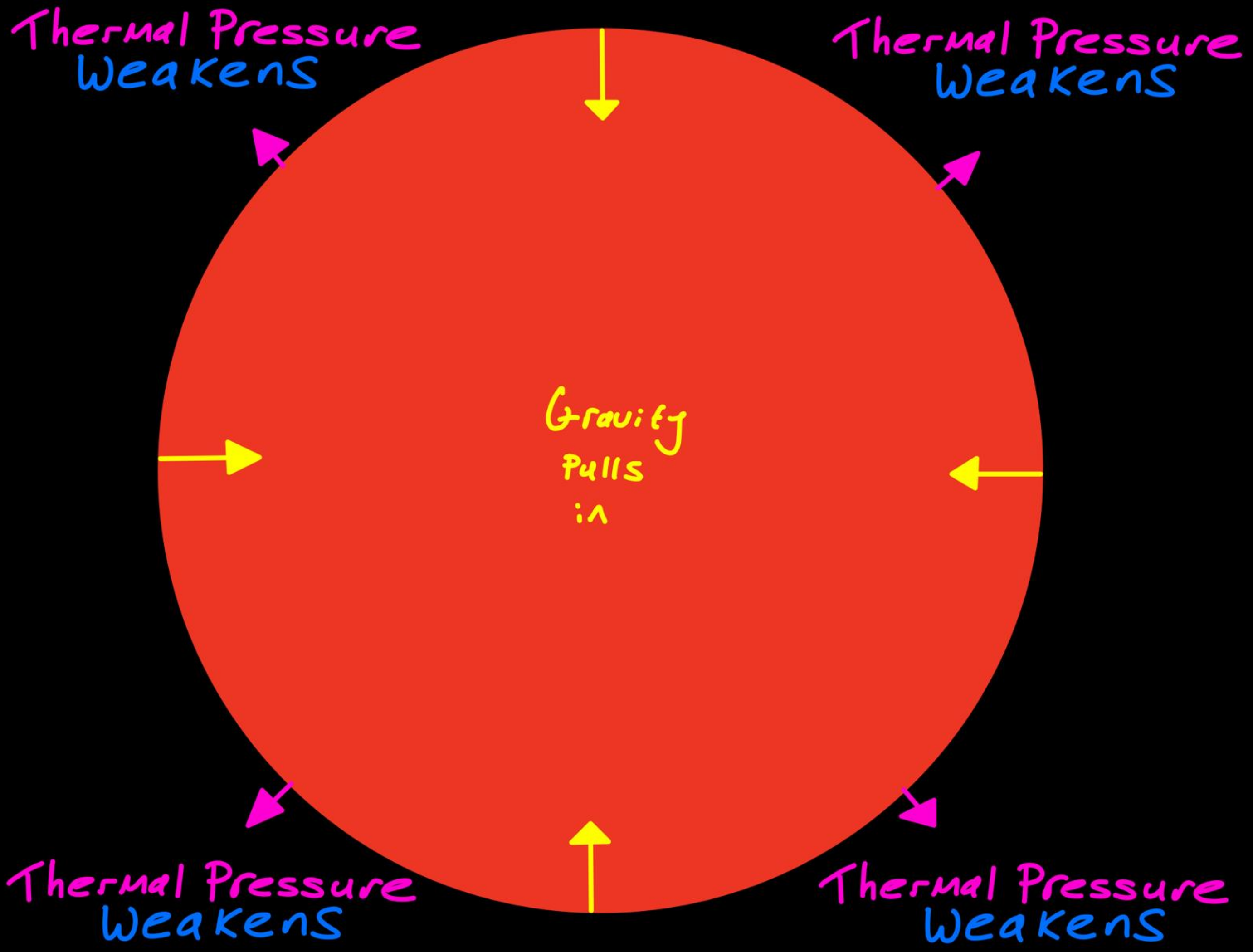


Death of a Star

When the core of a Supergiant Star turns to Iron, nuclear fusion can no longer continue.

Thermal Pressure drops, and gravity gets the upper hand.

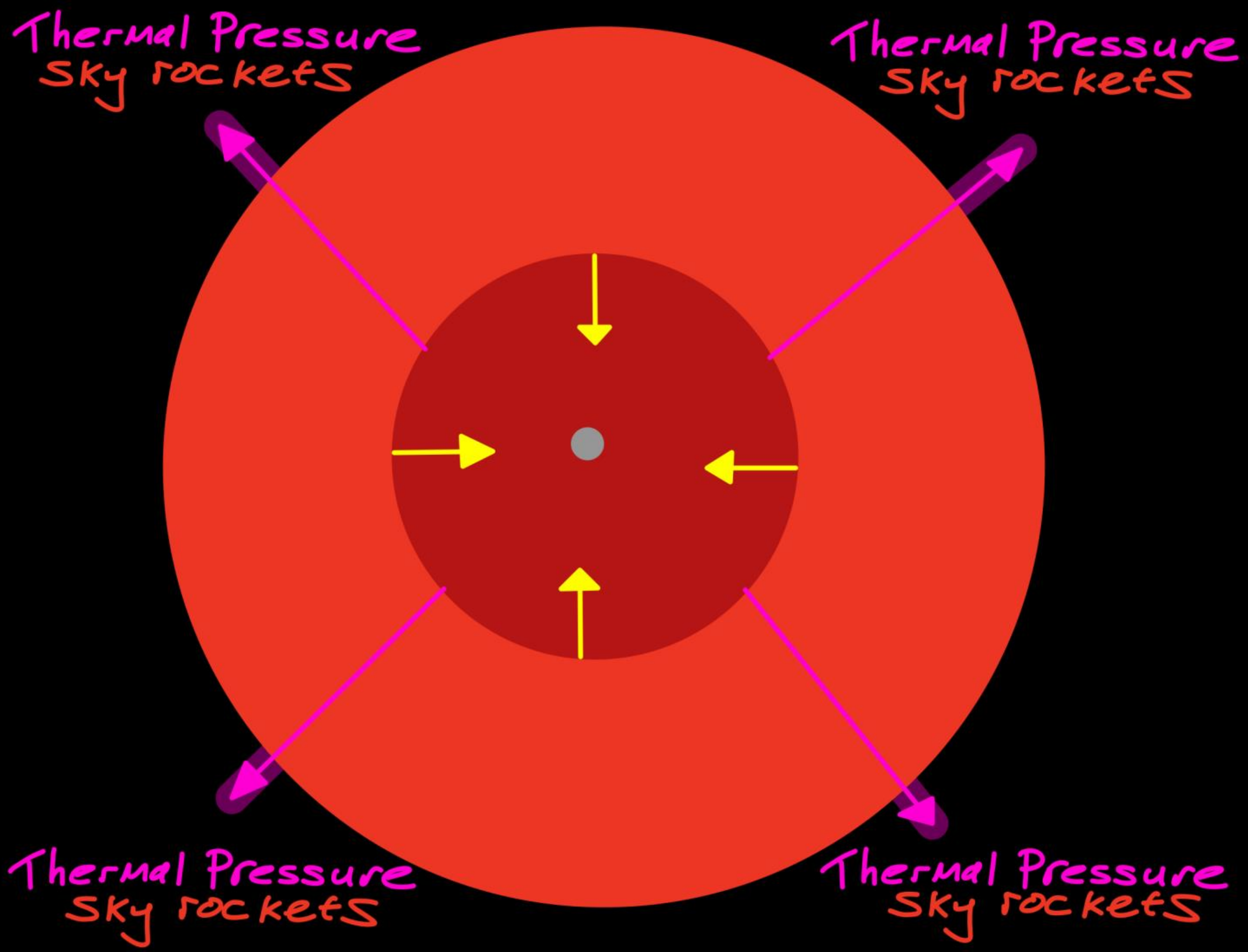
The core of the star collapses under the immense gravitational pull.



Death of a Star

During the collapse, the core releases a huge number of neutrinos.

The neutrinos deposit catastrophic levels of energy into the outer layers of the star, triggering an explosions (or type II **Supernova**).

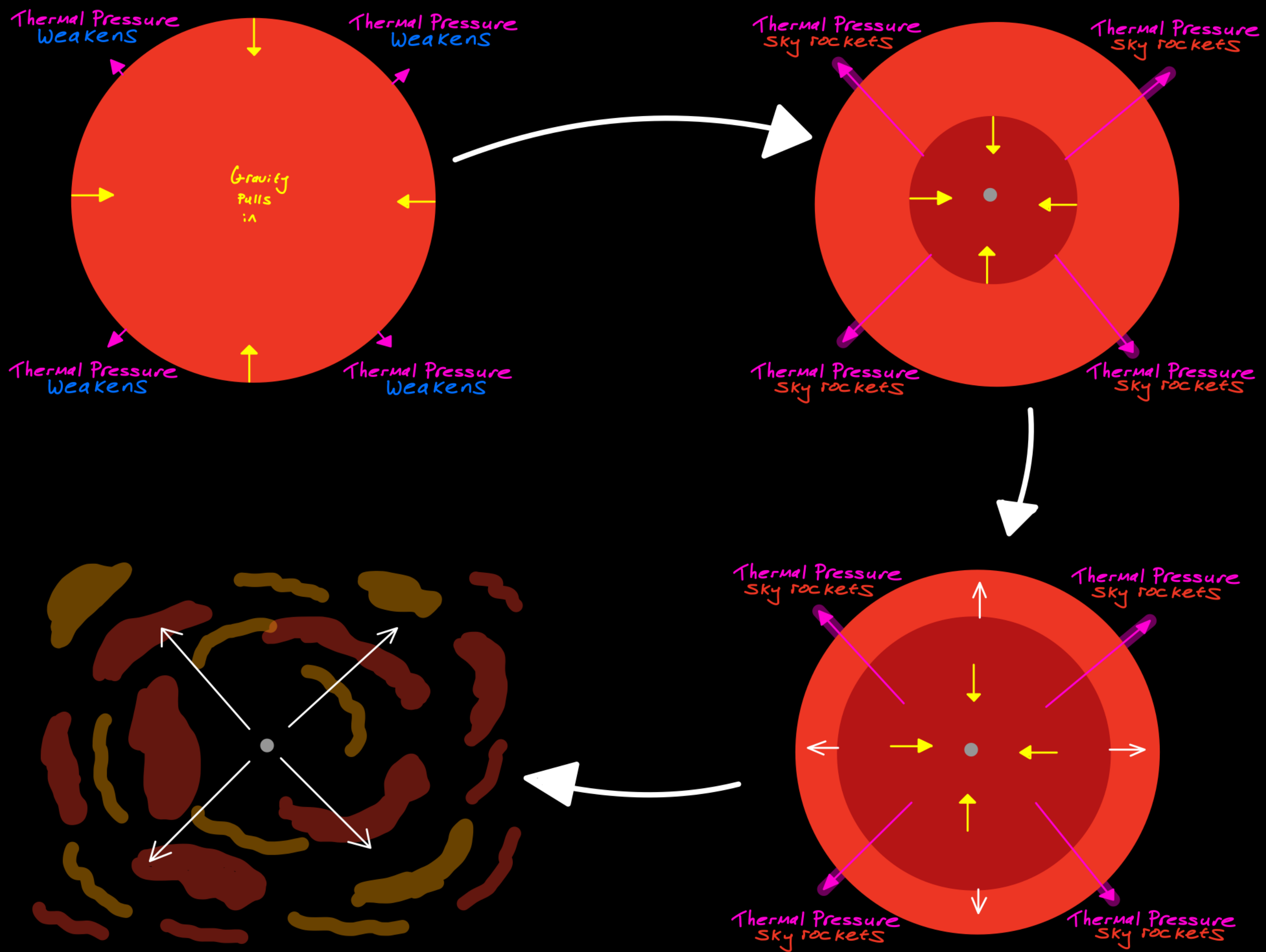


Death of a Star

The outer layers of the star explode out into space, forming a nebula and leaving behind a dead ***Stellar Remnant***.

There are three confirmed types of Stellar Remnant:

- White Dwarf Stars
- Neutron Stars
- Black Holes



Part III – Black Holes in the Cosmos

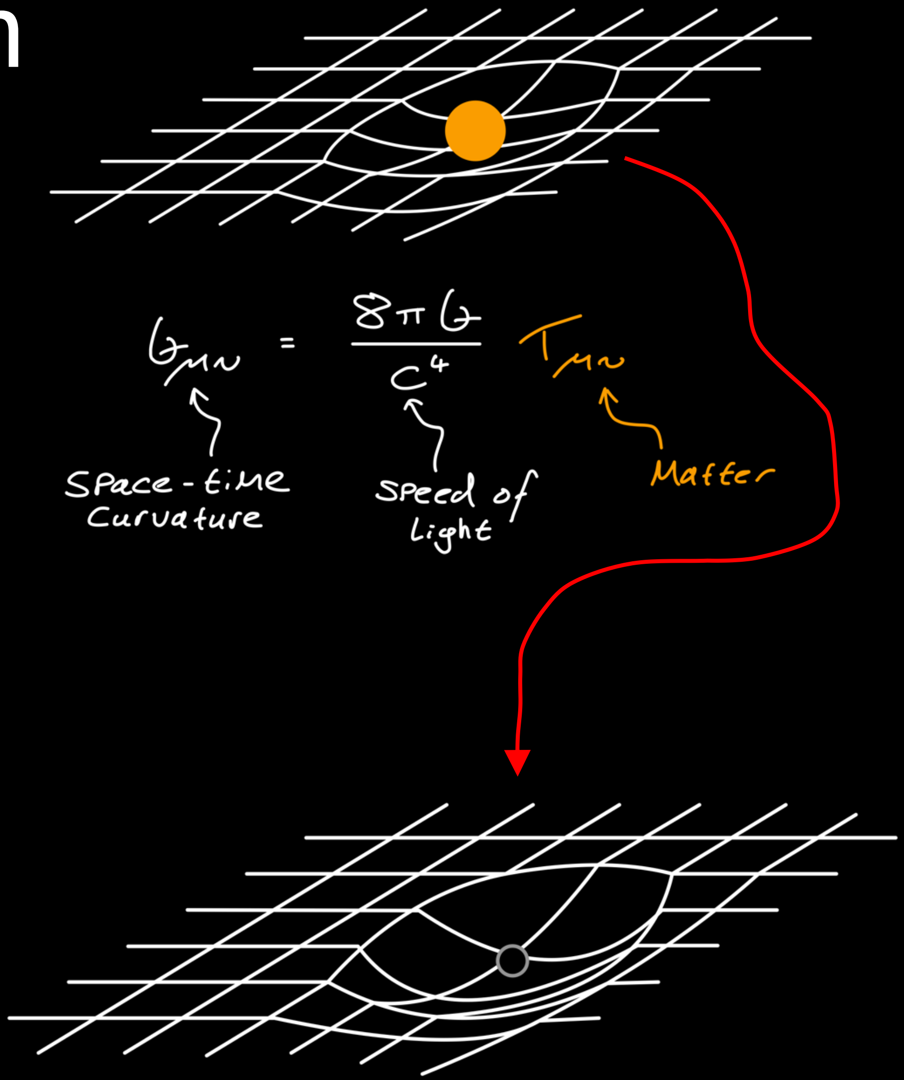
The Monster Hidden in the Equations

LLL [7-8]

Shortly after Einstein published his theory of gravity in 1915, Karl Schwarzschild finds the first mathematical solution to Einstein's equations.

Note: He does this while serving as an artillery officer during The First World War, in the misery of the German trenches. He writes to Einstein:

"As you see, the war treated me kindly enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas."



$$ds^2 = -\left(1 - \frac{2GM}{rc^2}\right)c^2 dt^2 + \left(1 - \frac{2GM}{rc^2}\right)^{-1} dr^2 + r^2 d\Omega^2$$

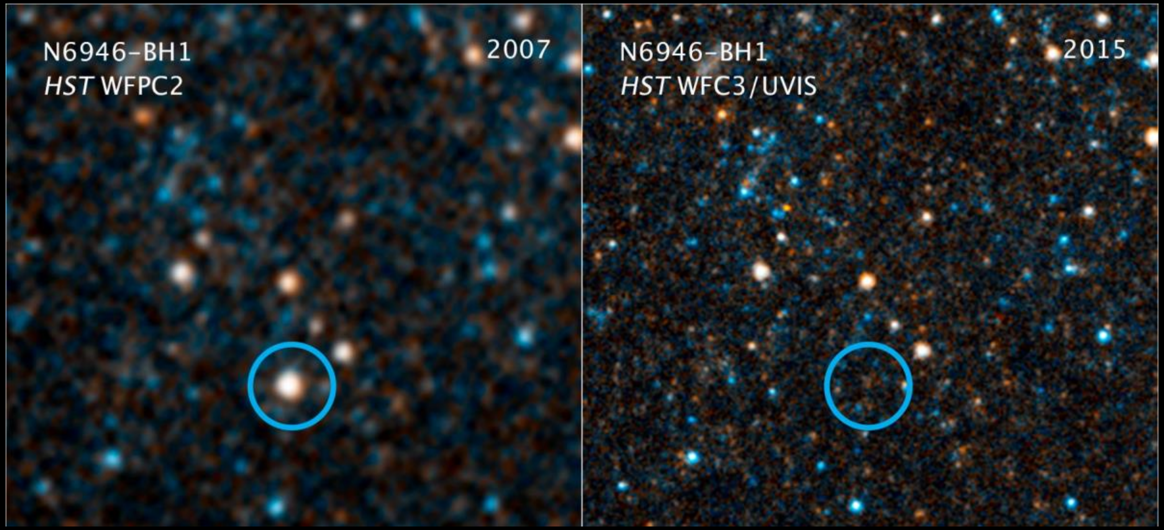
Karl Schwarzschild.

Birth of a Black Hole

LLL [9]

Taken to its ultimate conclusion, Schwarzschild's solution describes the end product of the interminable collapse of a massive star.

In 2009 astronomers believe this process was witnessed firsthand, when a supergiant star in the Fireworks Galaxy disappeared in a matter of years.

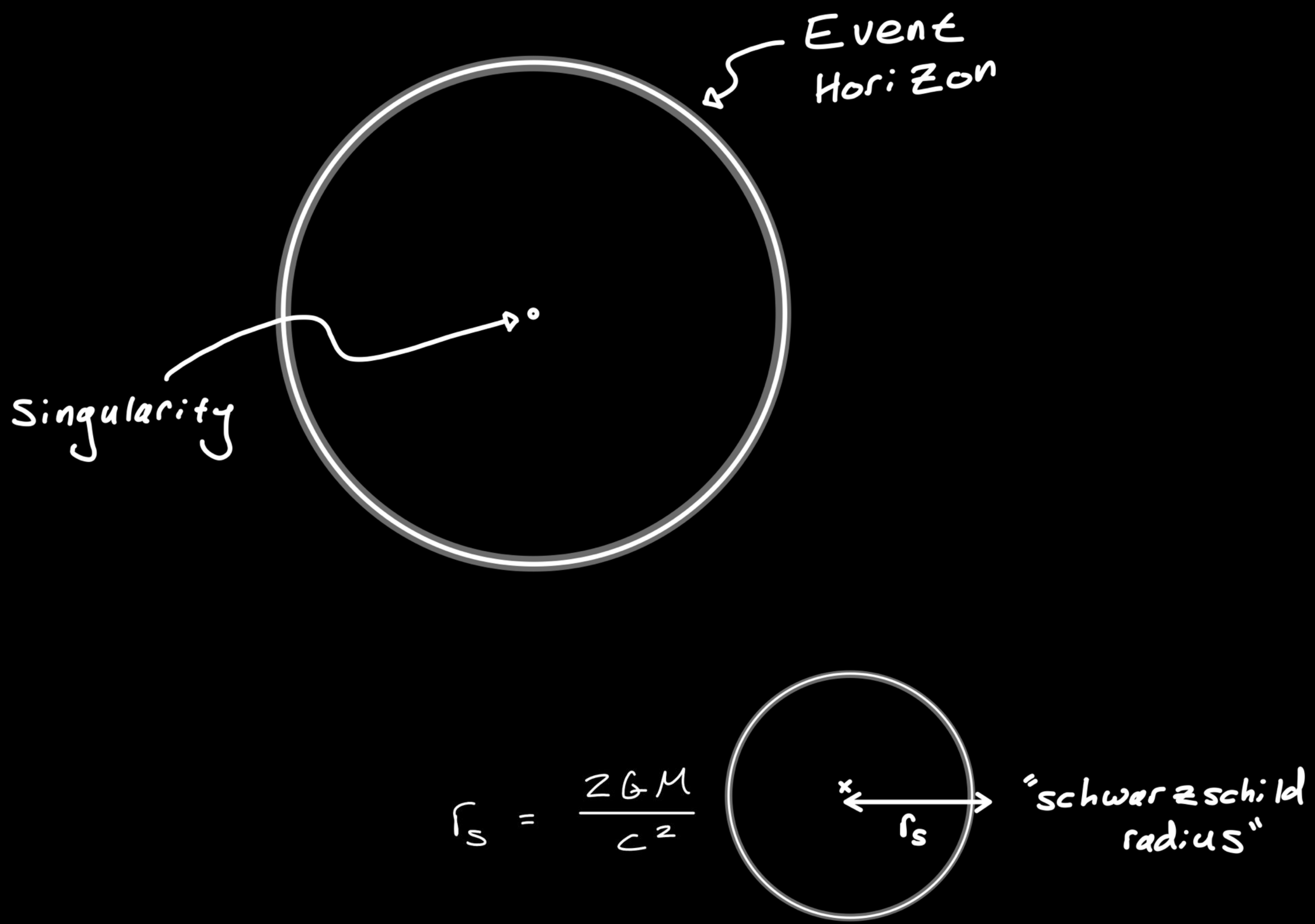


Pictures of N6946-BH1 before and after collapse into a Black Hole, taken with the Hubble Space Telescope.

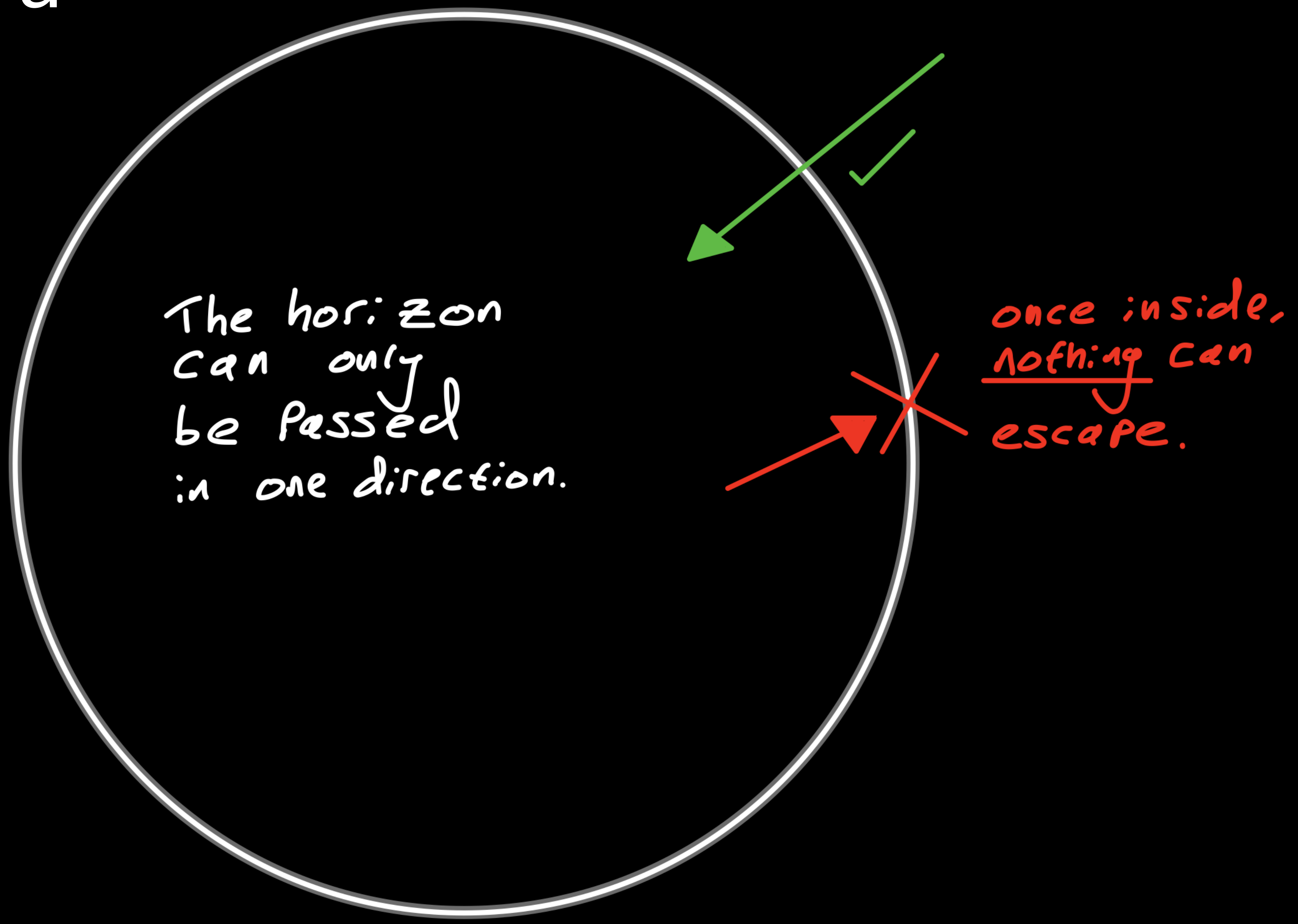
Illustration of the birth of a Black Hole, formed from a failed Supernova of a supergiant star in the Fireworks Galaxy.

Anatomy of a Black Hole

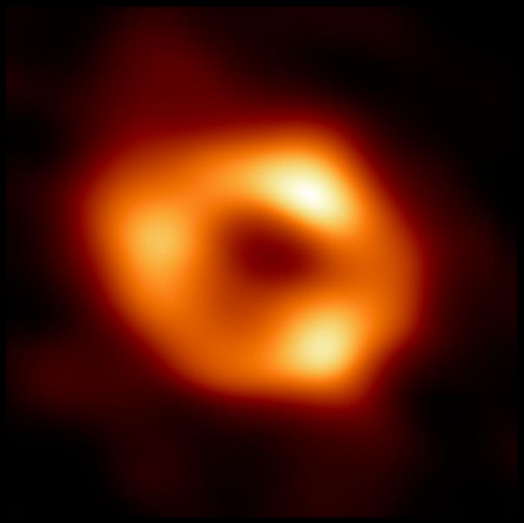
Describing a black hole is simple enough, as they have very few identifying features.



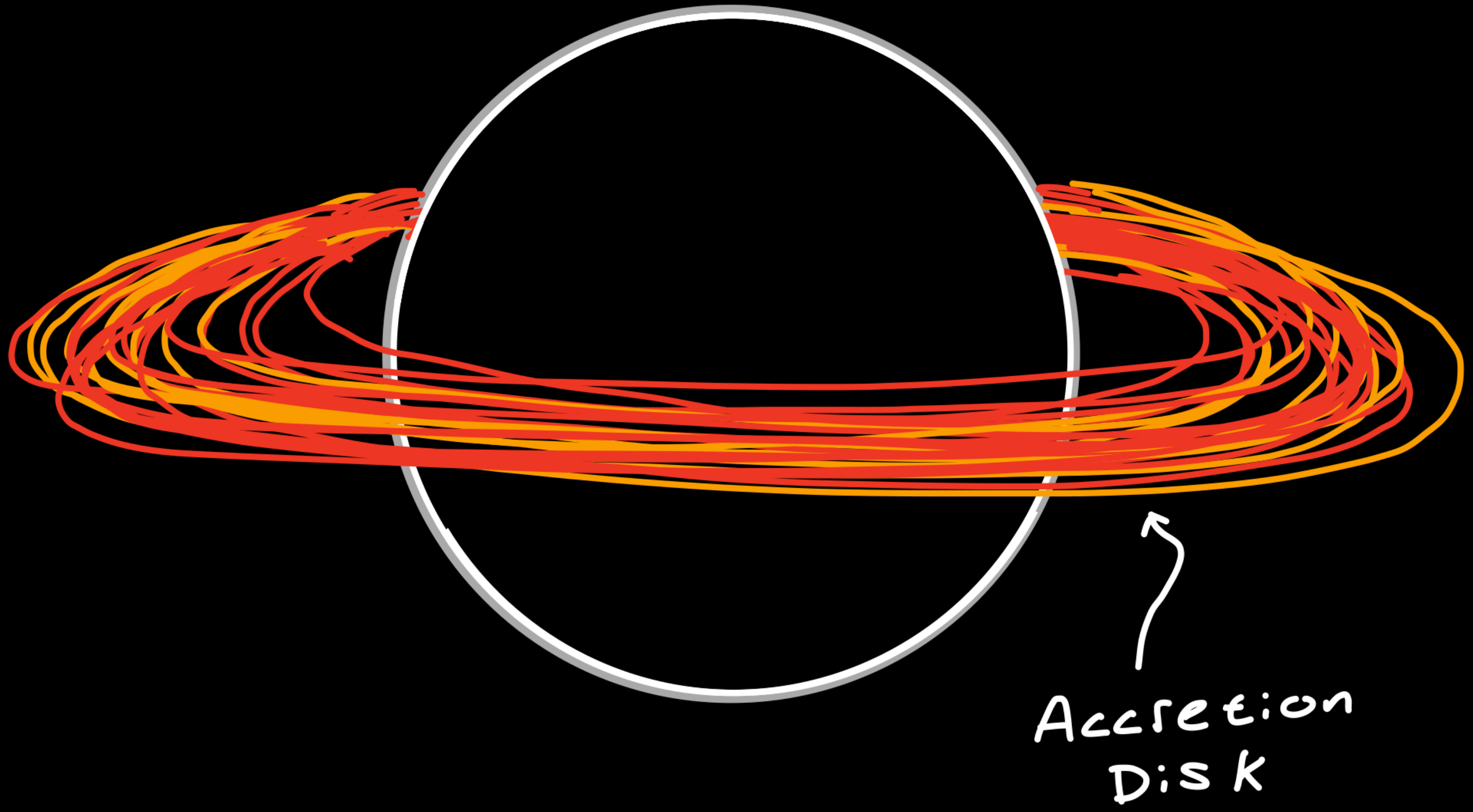
Anatomy of a Black Hole



Anatomy of a Black Hole

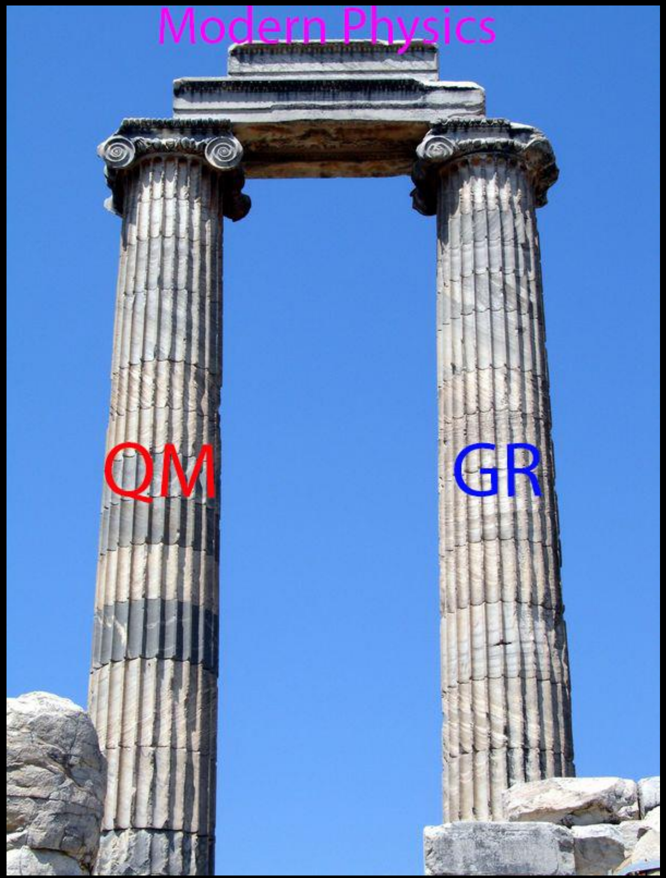


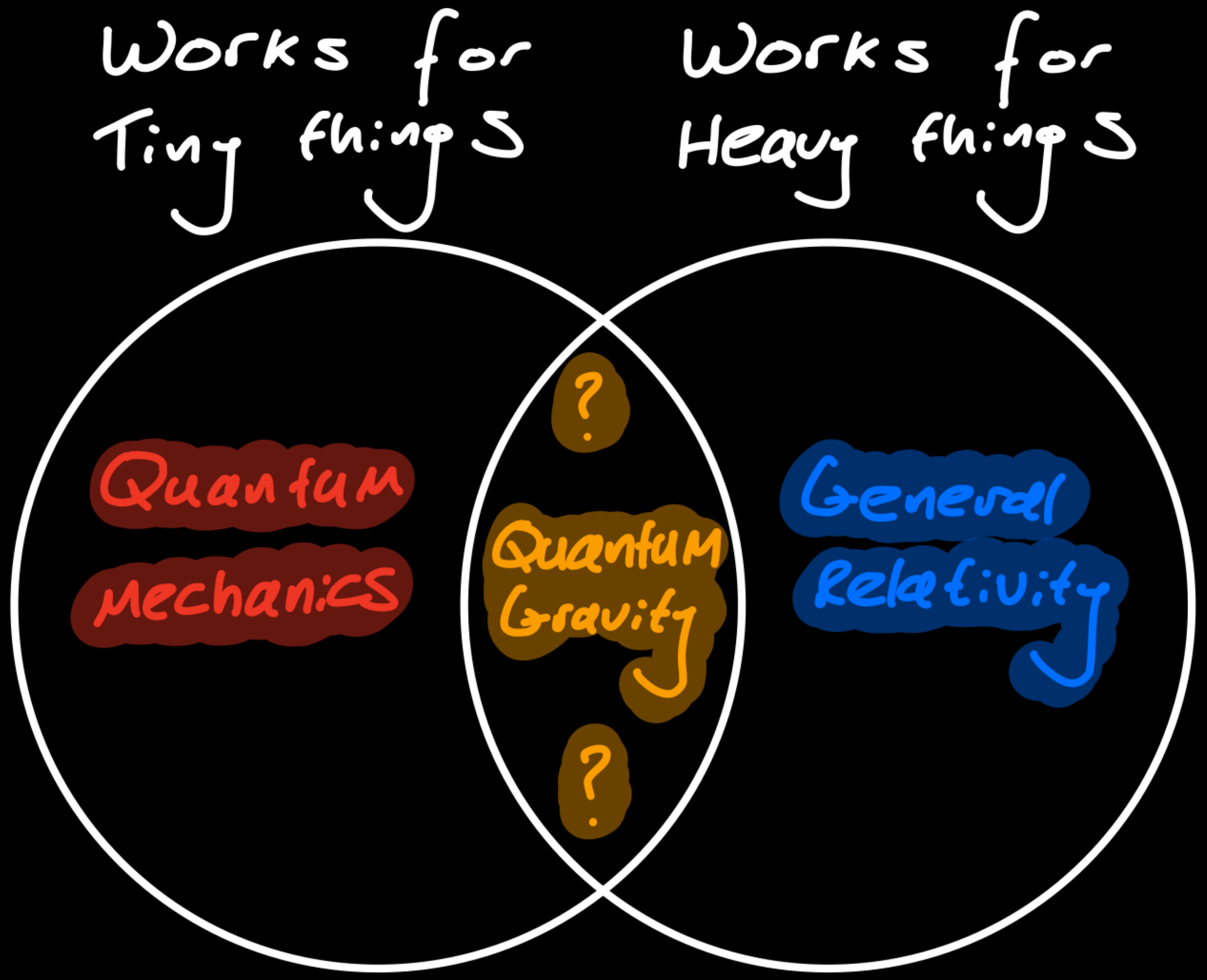
Event Horizon Telescope image of Sagittarius A*.



The Singularity

Why is the singularity so hard to understand?

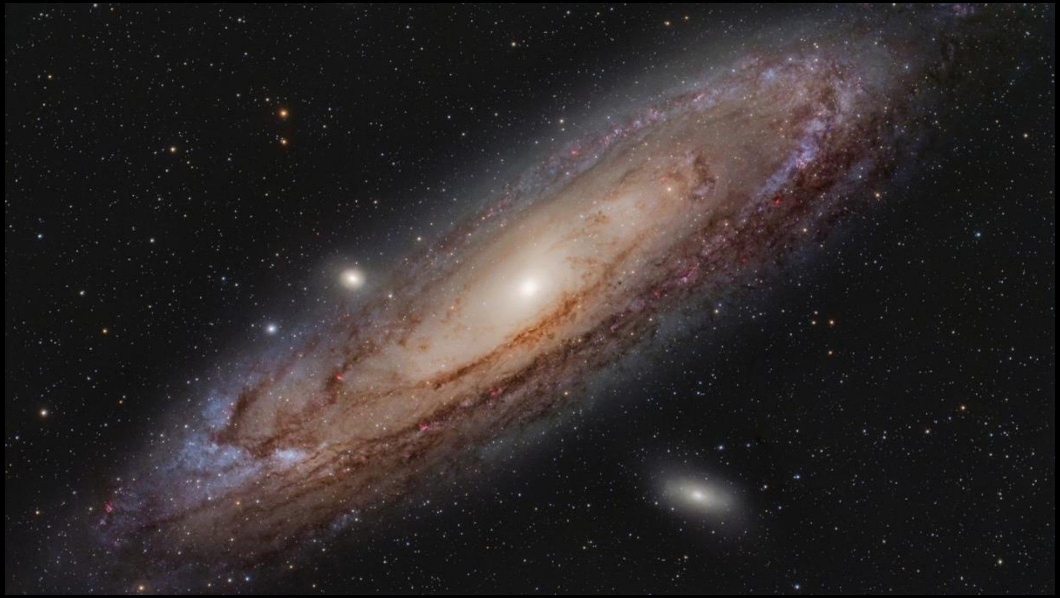




Supermassive Black Holes

Every large galaxy has a Supermassive Black Hole at its center.

An artist's impression of a Quasar, a particularly energetic kind of galactic nuclei.



The Andromeda Galaxy. The nearest neighboring galaxy to our own.

Black Holes are thought to be crucial to the formation of galaxies, in ways we don’t yet fully understand.

Note: Supermassive = Between one hundred thousand, and 1 billion times the mass of the sun.

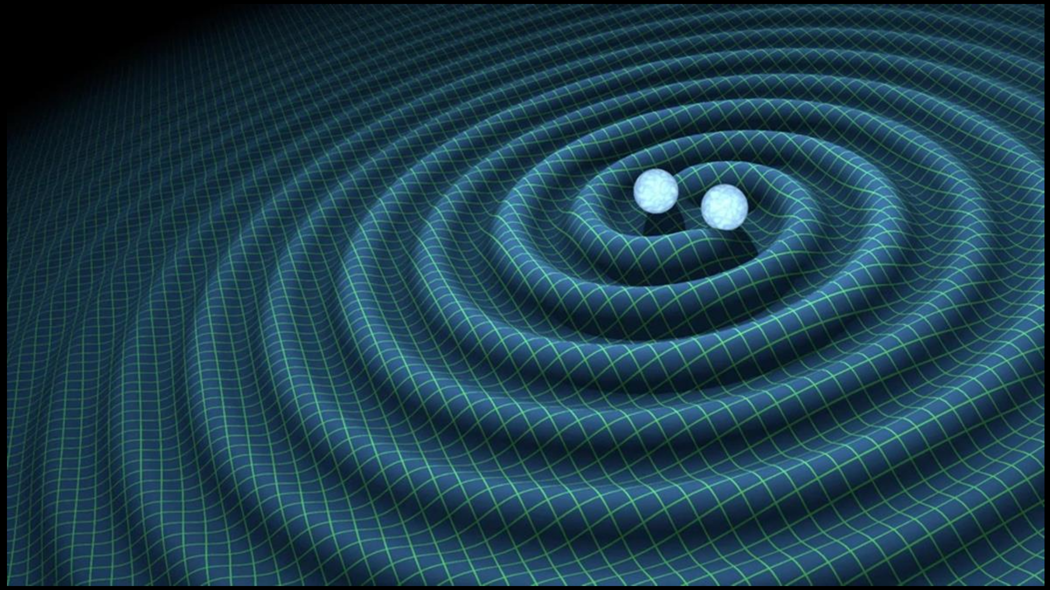
Observing Black Holes

Gravitational Waves

We now have numerous sources of observational evidence for the existence of black holes.

The first discovery of Gravitational Waves was announced in early 2016.

A prediction of General Relativity, these ripples in space-time could only have originated from the collision of two large black holes.



The ripples in space time, created by two colliding black holes.

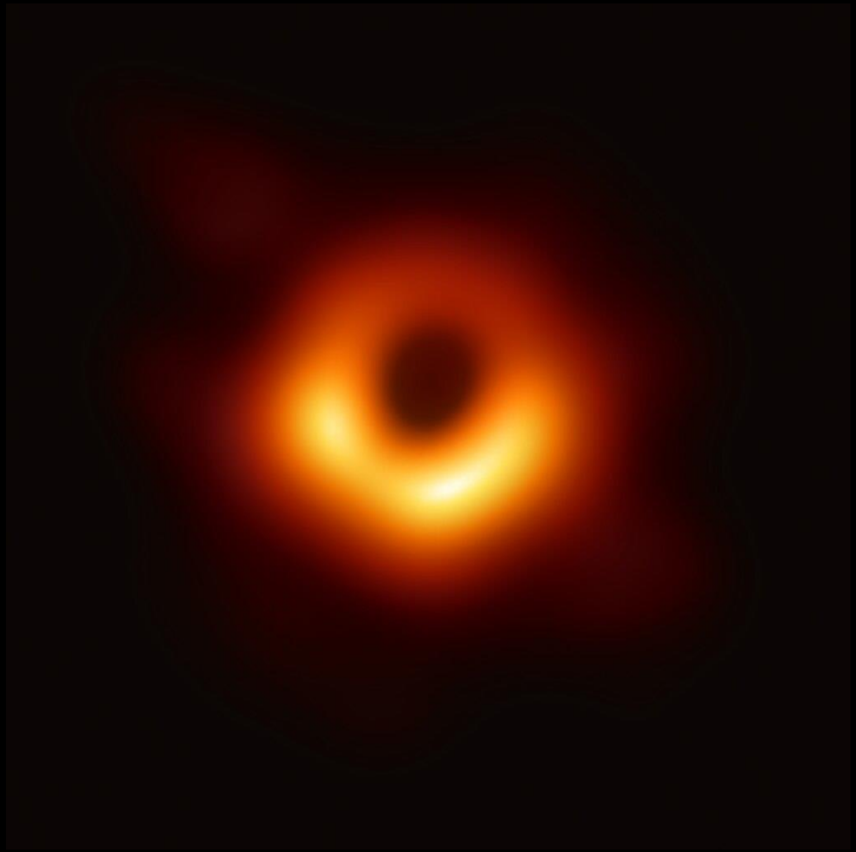
The LIGO Hanford facility in Washington State, US.

Observing Black Holes

Direct Imaging with the *Event Horizon Telescope*

In the last several years, we have even been able to observe black holes directly using the event horizon telescope array (EHT).

The EHT combines data from numerous radio telescopes around the world.



The first image of M87* (the supermassive black hole at the center of the Messier 87 galaxy.

Observing Black Holes

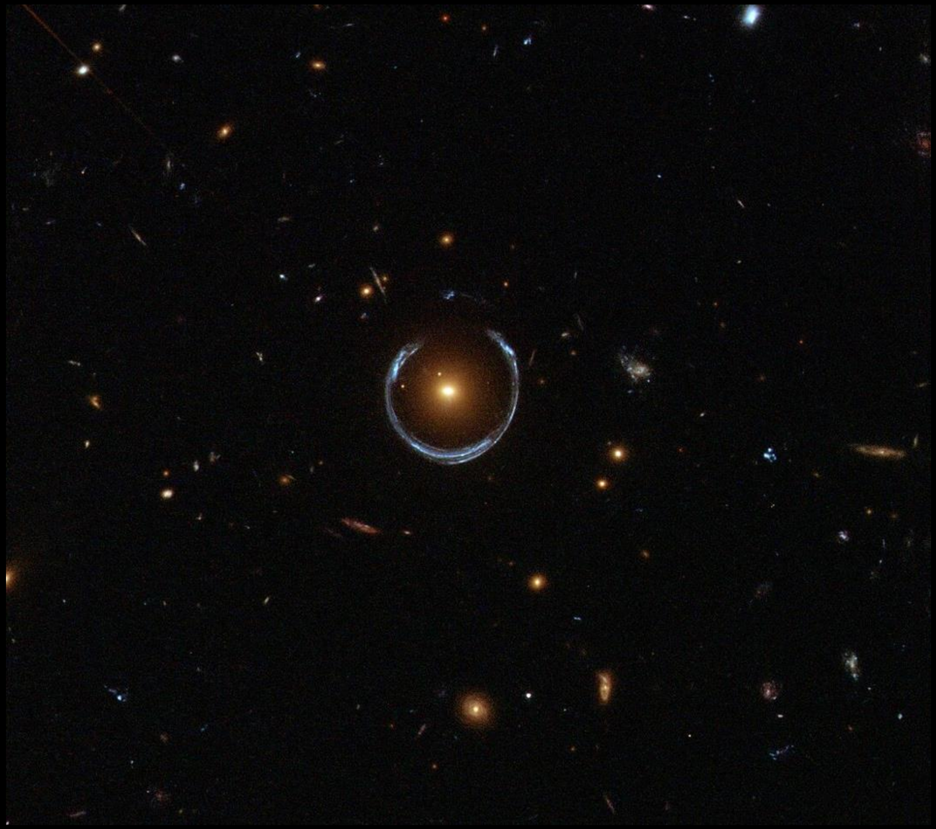
LLL [10]

Gravitational Lensing

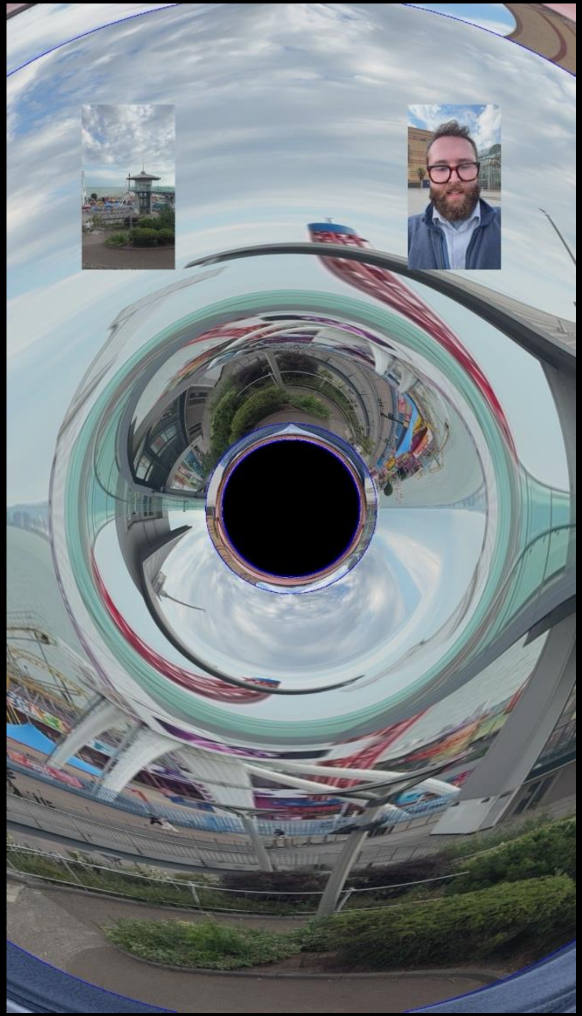
The Spacetime distortion around a Black Hole is so intense, that is affects the path of light around it.

‘Einstein Rings’, such as the Cosmic Horseshoe are indicative of very large black holes.

The blueish ring of the Cosmic Horseshoe is a distorted image of a galaxy behind an ultra-massive black hole.



The ‘Cosmic Horseshoe’ in the constellation Leo

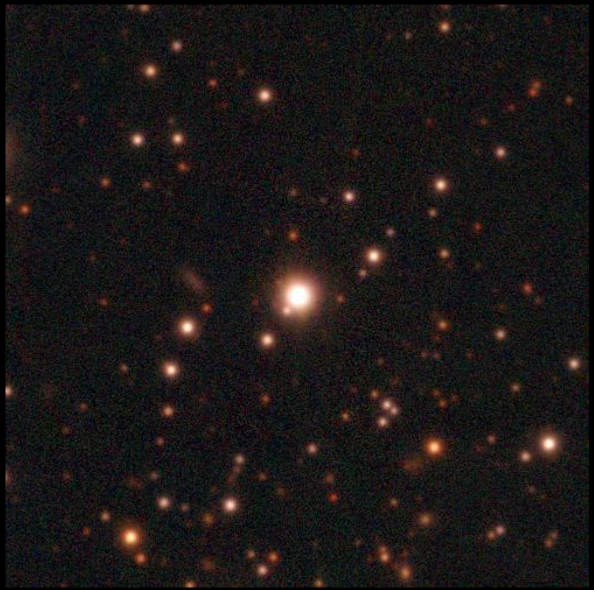


Black Hole Selfie on Pier Hill

Our Nearest Neighbor

1560 light-years away, a star very similar to our own sun orbits around a black hole.

This black hole has a mass nearly ten times greater than our sun.



Pan-STARRS image of the Gaia BH1 system.

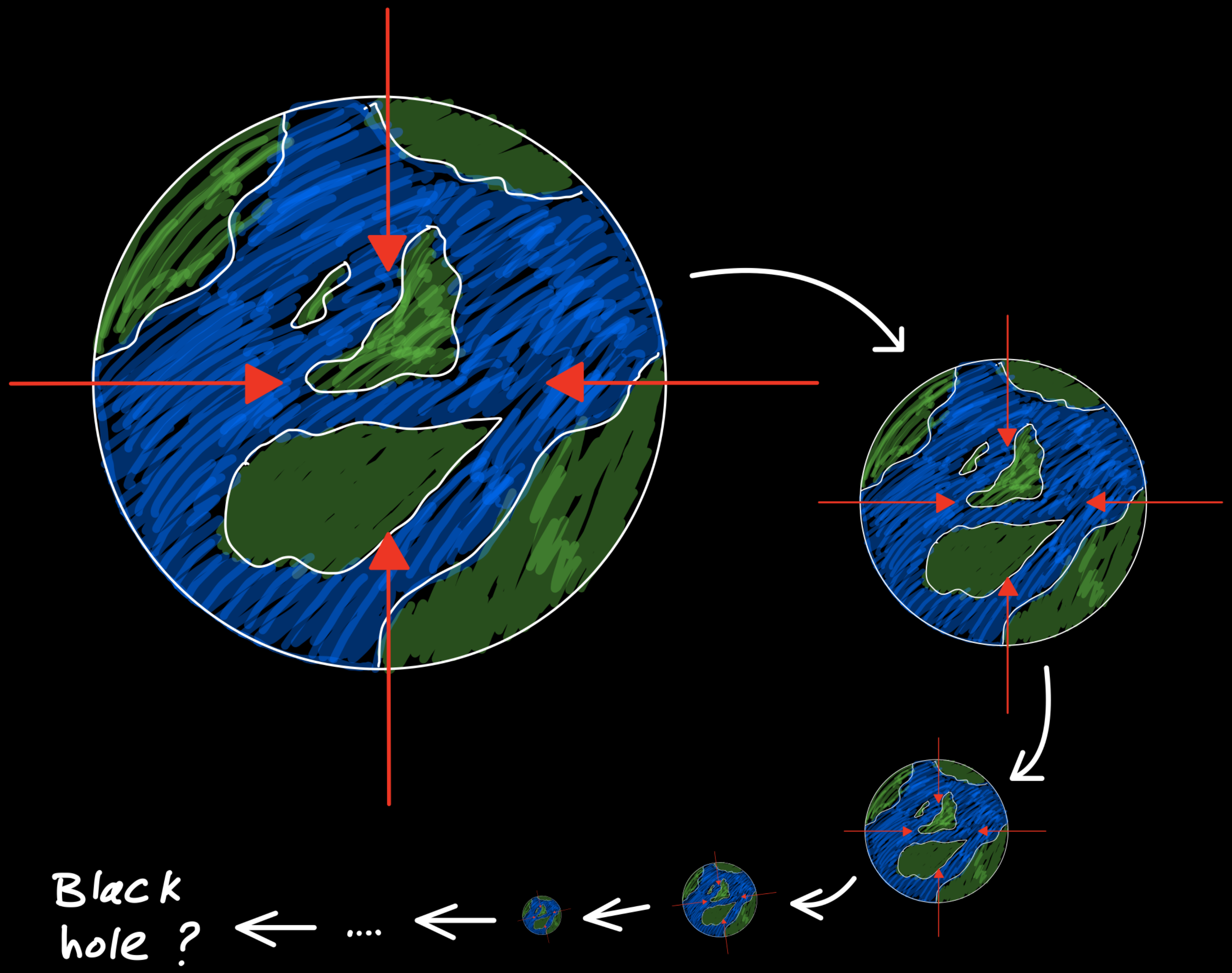
This is the size of our nearest black hole (Gaia BH1), compared to Essex.

The radius stretches roughly from the Beecroft Gallery to the Dartford Bridge.

A Sense of Scale

Let's squash the Earth down until it turns into a black hole.

How far would we need to squash it?



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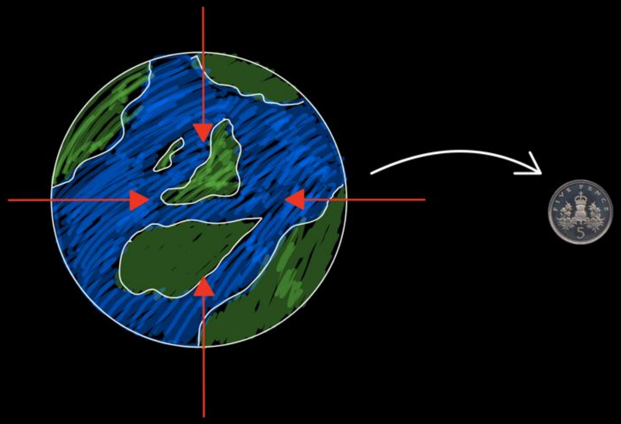


Earth Mass Black Hole

$$M_{Earth} = 5.97 \times 10^{24}\ kg$$

$$r_s = \frac{2GM}{c^2} = \frac{2 \times 6.67 \times 10^{-11} \times 5.97 \times 10^{24}}{(3 \times 10^{8})^2}$$

$$= 8.85 \times 10^{-3}\ m$$

$$= 8.85\ mm$$

$\Rightarrow$ Diameter $\simeq$ 18mm

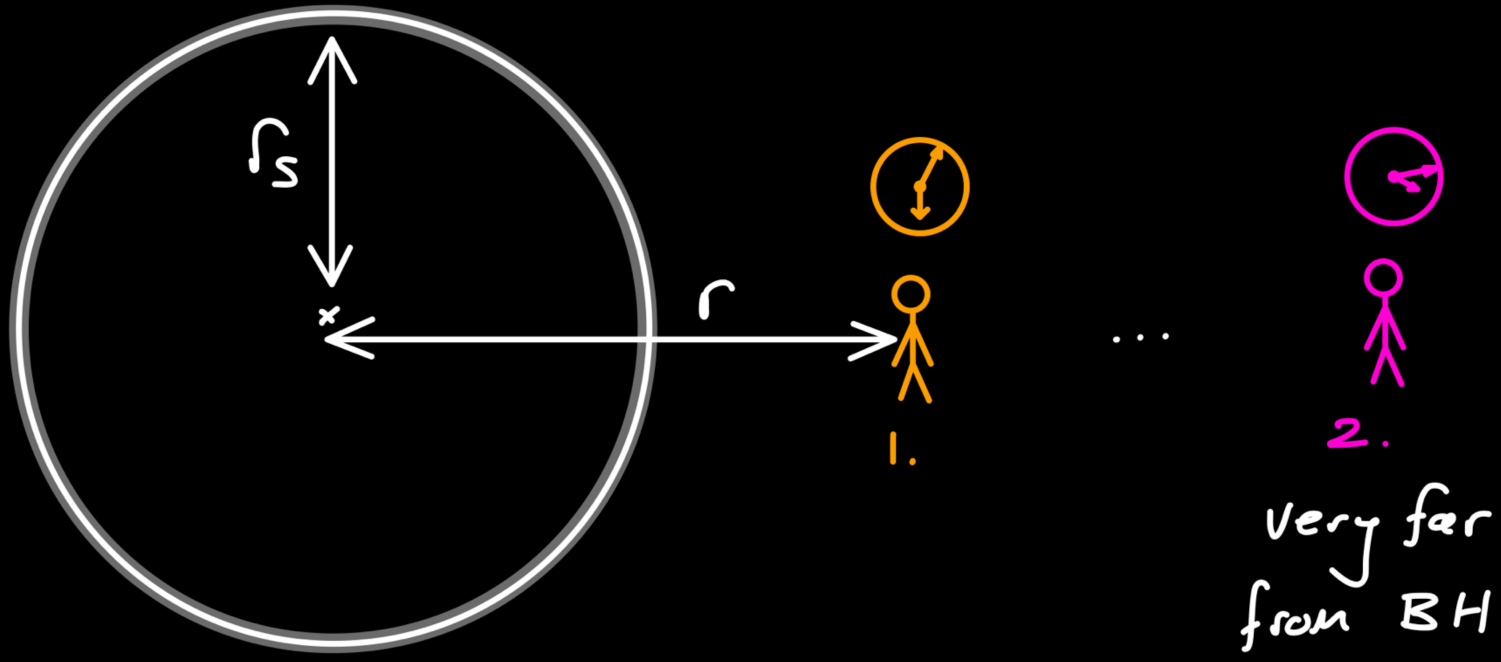
About the same as a 5p coin.

Part IV – Black Holes as Time Machines

Natural Time Machines

Perhaps the strangest property of black holes, is how the bend and stretch time for those nearby…

$$\Delta t_{near} = \Delta t_{far}\sqrt{1 - \frac{r_s}{r}}$$



Person 2's clock will tick much faster than Person 1's.

Let's put this into perspective using Gaia BH1, the nearest known black hole to the Earth.

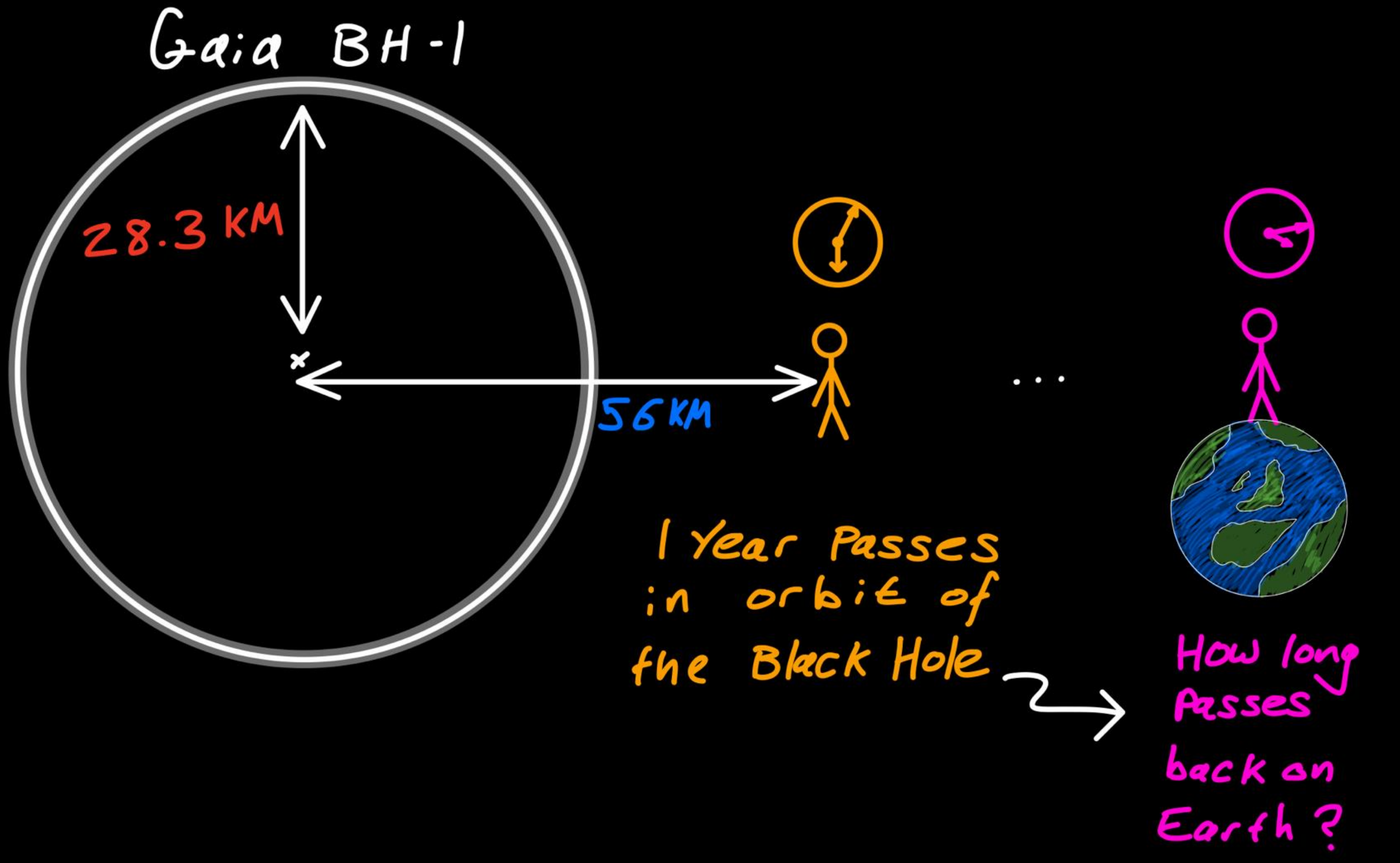
Natural Time Machines

Recall, Gaia BH1's radius stretched out to Dartford.

Suppose we get into an orbit that would stretch out to central London.

Natural Time Machines

Spend 1 year orbiting our nearest known black hole, and you will have travelled forwards in time by 5 months compared to everyone home on Earth.



$$\Delta t_{Earth} = \frac{1\,yr}{\sqrt{1 - \frac{28.3\,km}{56\,km}}} = 1\,yr + 5\,months$$

Part V – Death by Black Hole

TDE's

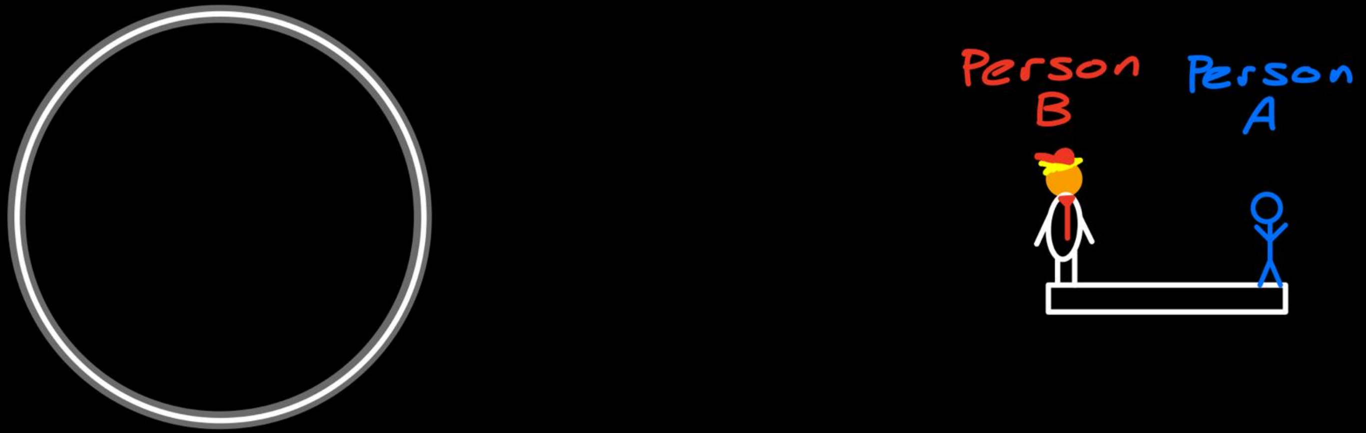
A ***Tidal Disruption Event*** is one of the most intense ways a Black Hole can cause destruction.

If a star moves too close to a very large black hole, the *tidal forces* pulling on the star can cause it to disintegrate entirely.

Simulation of a TDE (Tidal Disruption Event) [NASA, ESA, STScI, Ralf Crawford (STScI)]

Death by Black Hole

Person A pushes Person B into a black hole.



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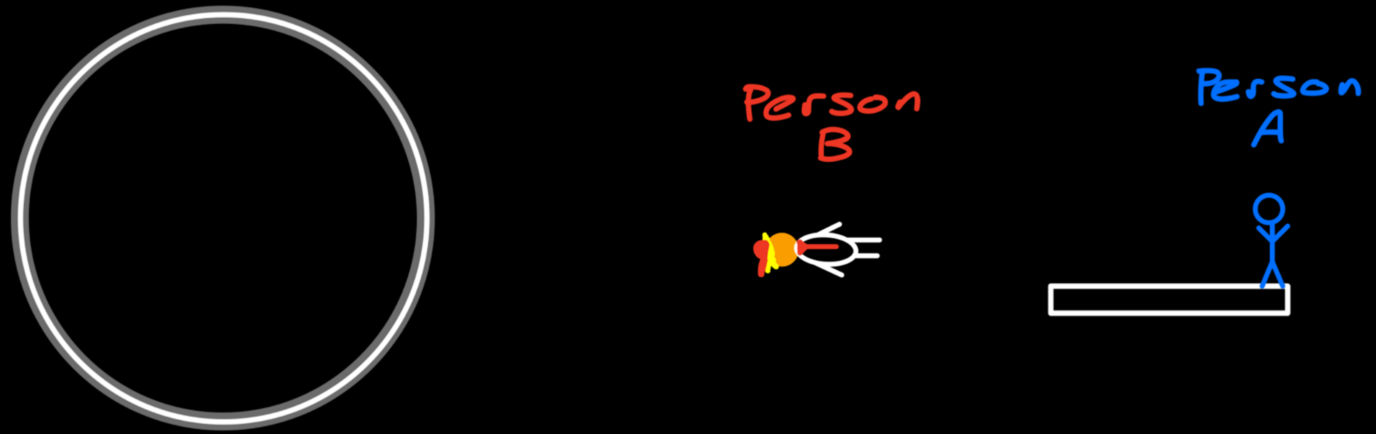


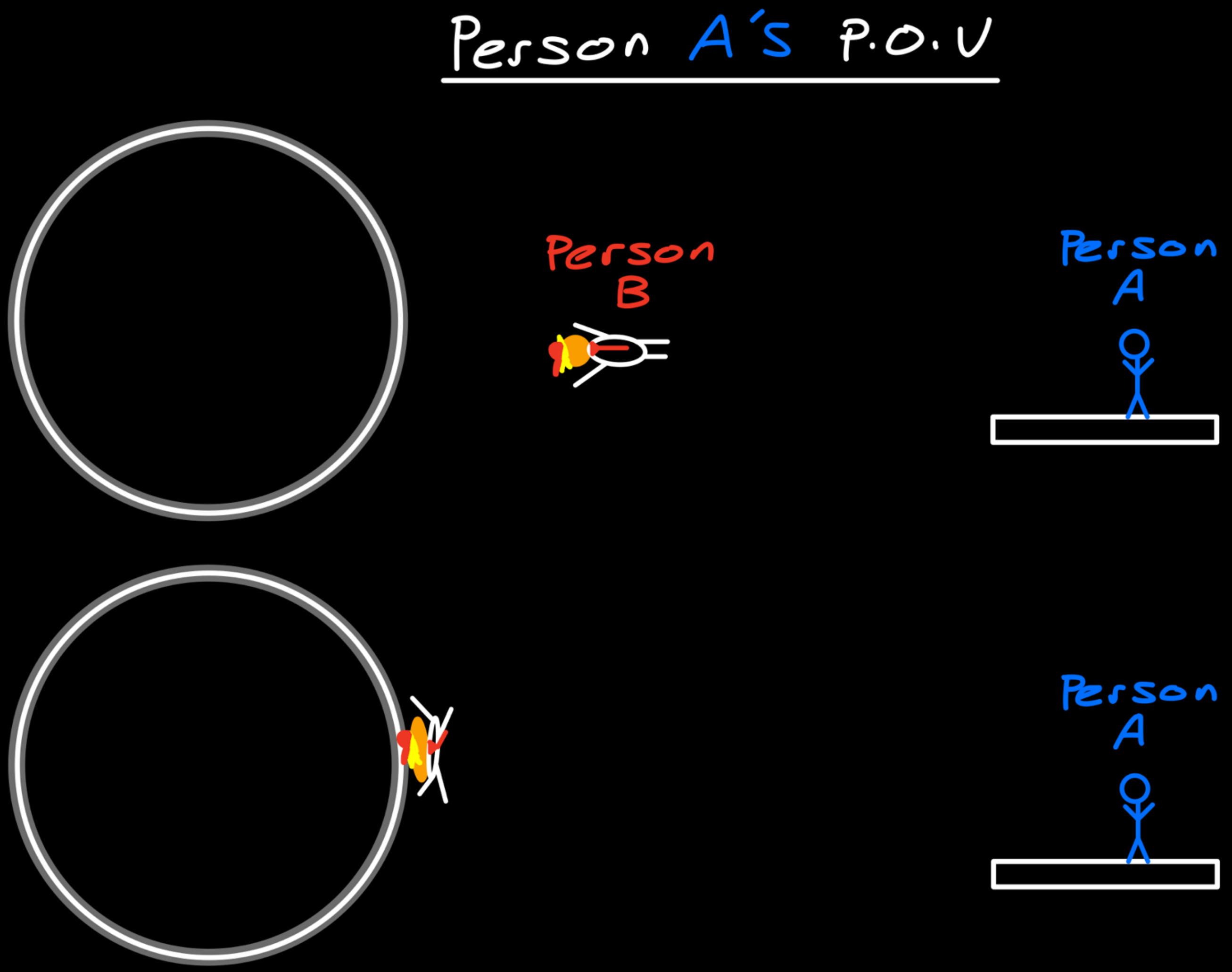
Let's consider how this looks to each person involved…

Death by Black Hole

Person A's POV

From Person A's POV, person B never crosses the event horizon.

Instead, Person B smears along the horizon, become flatter and flatter over billions of years.



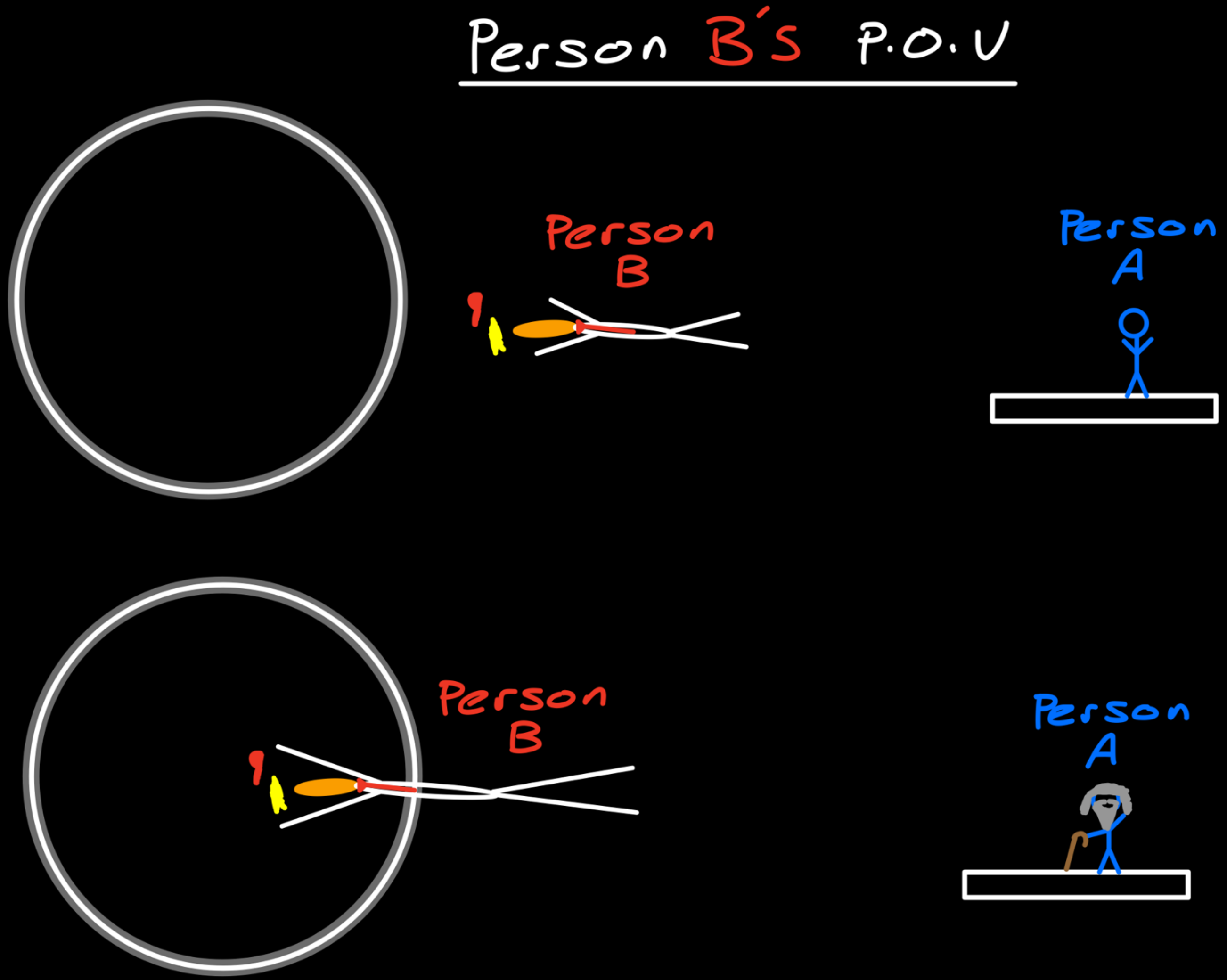
Death by Black Hole

Person B's POV

From Person B's POV, they pass through the horizon without much difficulty.

If the black hole is very small, they will be 'spaghettified' by the fall.

As Person B looks back at Person A, A begins to age rapidly.



Part VI – Death of a Black Hole

Death ***of a*** Black Hole

LLL [11]

In 1974, Stephen Hawking showed that Black Holes can in fact radiate particles, and hence reduce their size.

The radiation they release is called Hawking Radiation.

This process is **extremely** slow.

A black hole with the mass of our sun (impossibly tiny for a naturally occurring black hole) would take 10^{67} years to fully evaporate.

Stephen Hawking with a group of young physicists (including a 19-year-old me!), 2016.

Hawking Radiation

To understand Hawking radiation, we need to combine two key ideas in 20th century physics. Quantum Mechanics & Special Relativity.

'Fundamental Uncertainty' is an unavoidable aspect of Quantum Theory.

This uncertainty is described by Heisenberg's Uncertainty Principle(s).

The more accurately we measure *how much* energy there is, the less sure we can be about *how long* that energy is present.

One version of Heisenberg's Uncertainty Principle:

$$\Delta E \, \Delta t \gtrsim \frac{\hbar}{2}$$

$\Rightarrow$ We can 'borrow' energy from the vacuum, just so long as we return it quickly...

Hawking Radiation

During Einstein's *annus mirabilis* of 1905, in which he published four ground-breaking papers, he discovered his famous relation between mass and energy.

This relationship laid the foundation for the nuclear age, and our understanding of how the stars shine.

Einstein's famous formula, from his special theory of relativity:

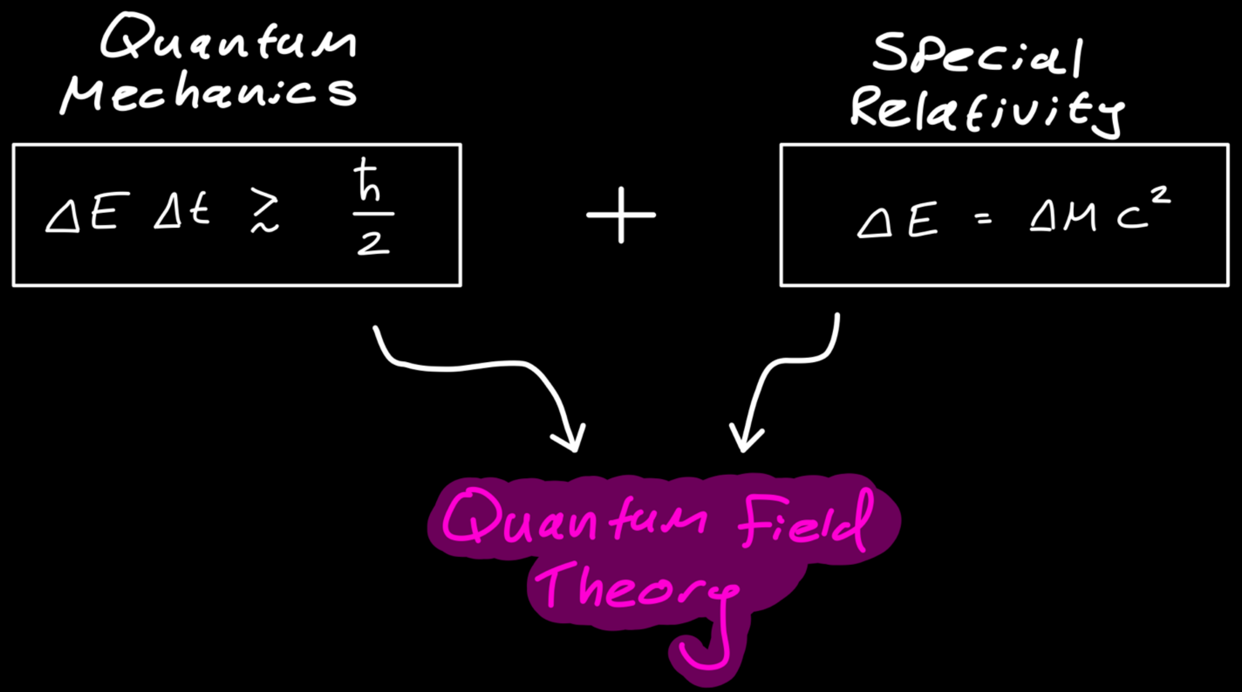
$$\Delta E = \Delta m c^2$$

⇒ Matter and Energy are interchangeable.
We can 'buy' matter by 'spending' energy.

Hawking Radiation

LLL [12]

The fusion of Quantum Mechanics and Special Relativity leads to our most complete theory of nature yet, Quantum Field Theory.

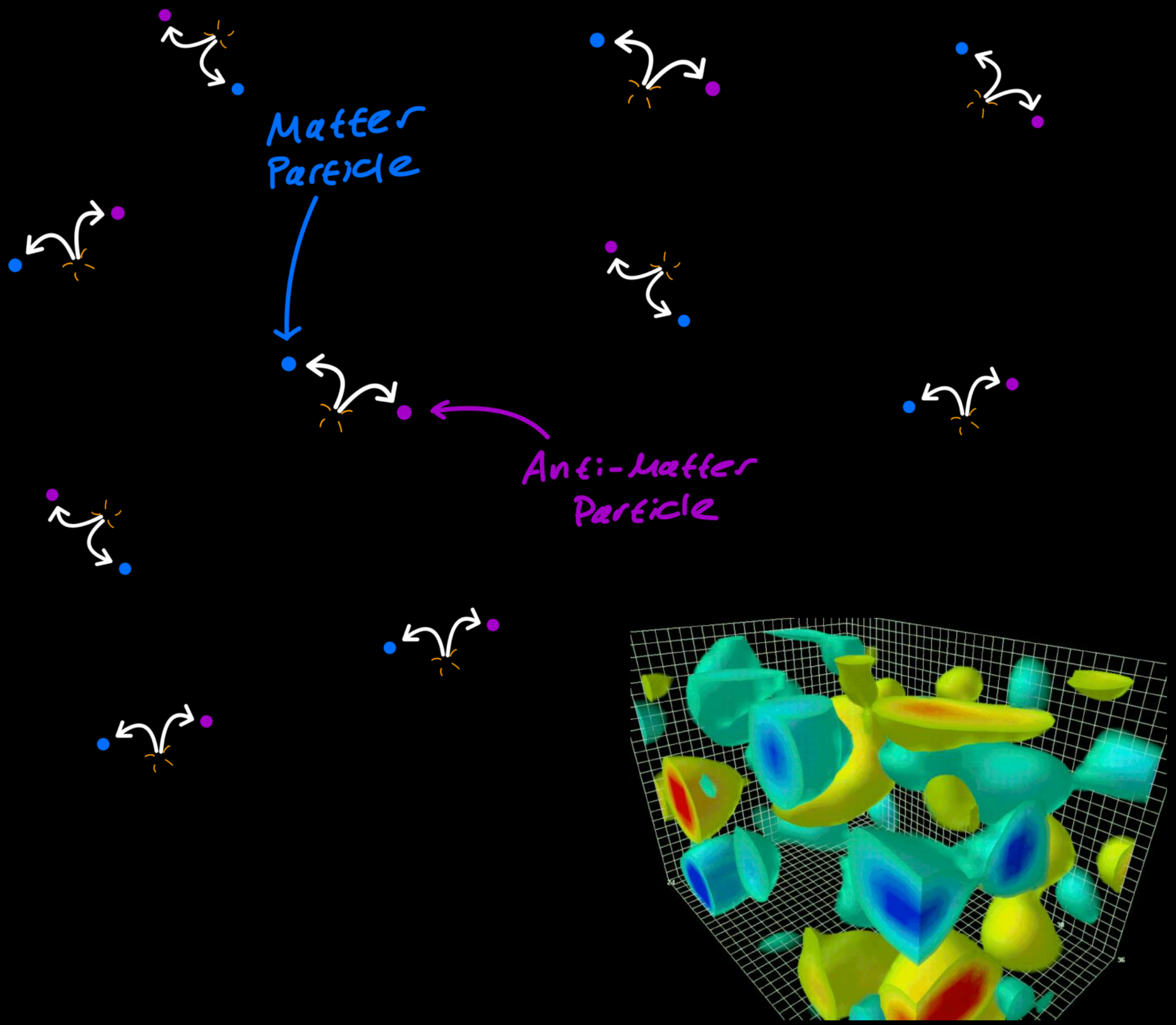


Hawking Radiation

Quantum Field Theory describes matter particles, at the most fundamental level, as excitations of some undulating underlying ‘*Quantum Fields*’.

Particles pop into existence and dissolve back into the vacuum a short time later.

This *fizz* of of creating and annihilating particles fills the entire Universe.



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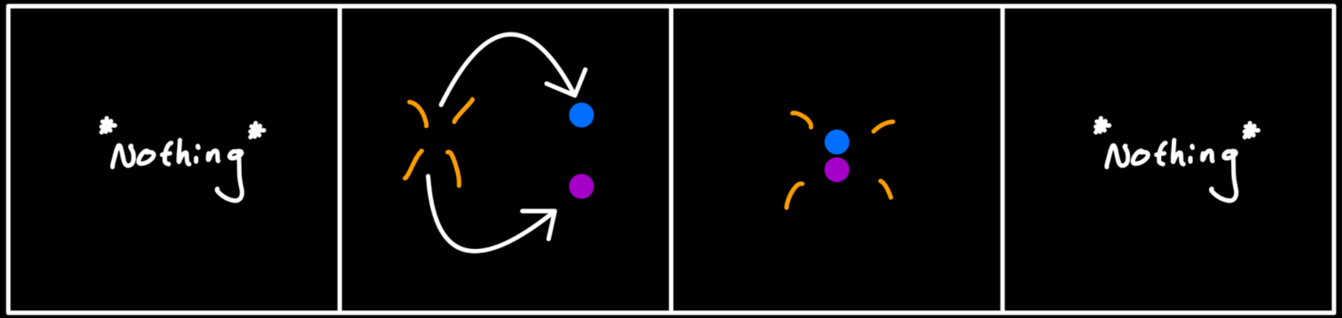
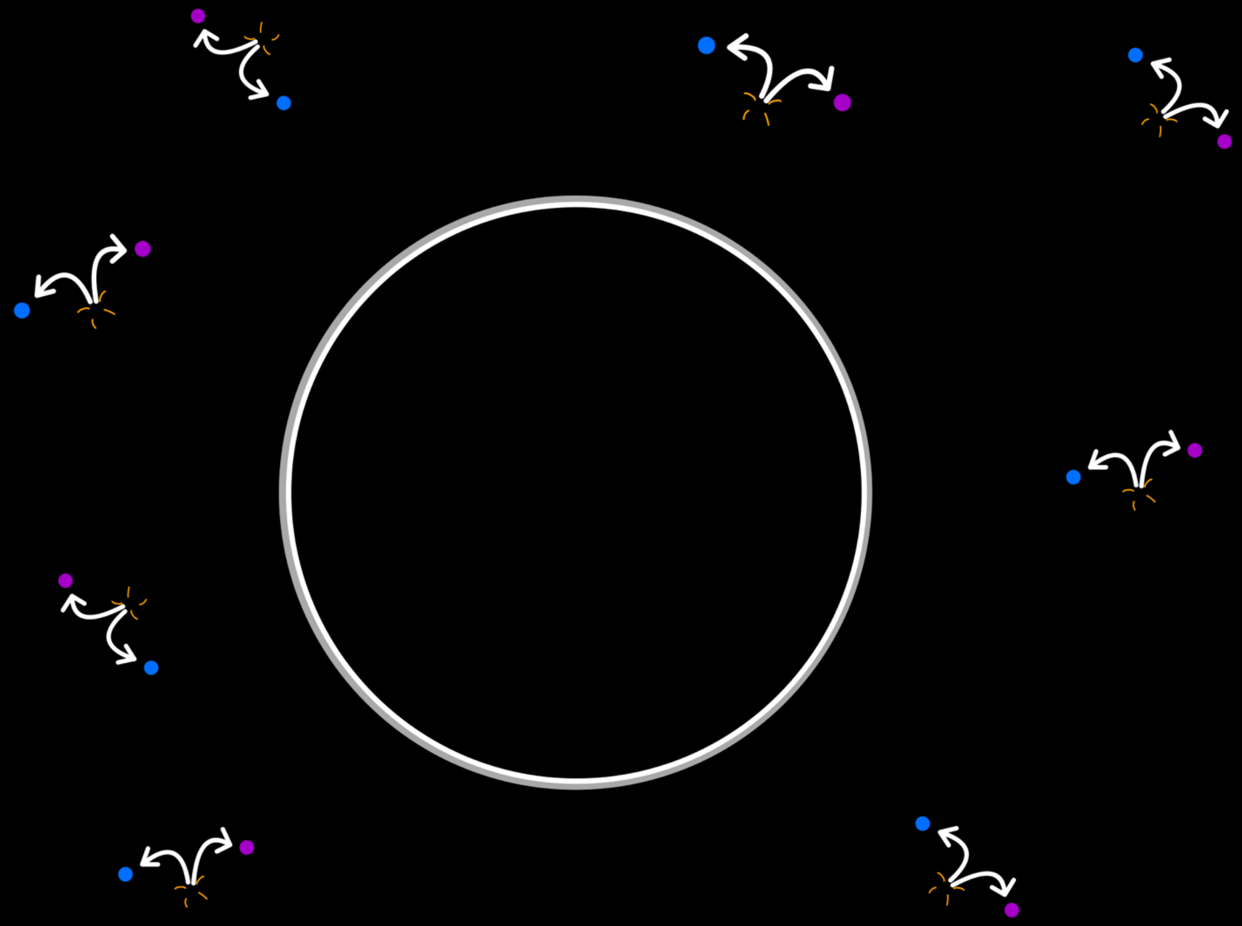


Thanks to Heisenberg's Uncertainty Principle, we can break the law of energy/mass conservation – so long as we don't break it for very long!

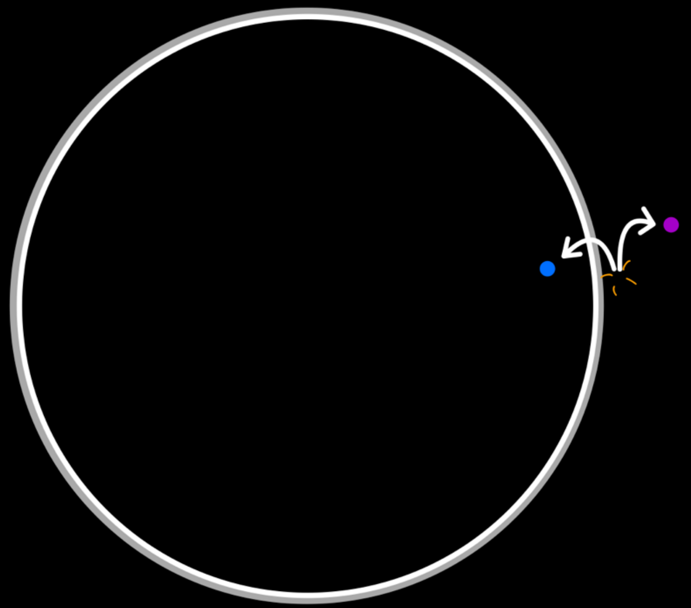
Hawking Radiation

These ‘*Quantum Fluctuations*’, of particles popping in and out of existence occur around black holes too.



Hawking Radiation

What happens if one of the particles produced in these quantum fluctuations falls into the black hole?

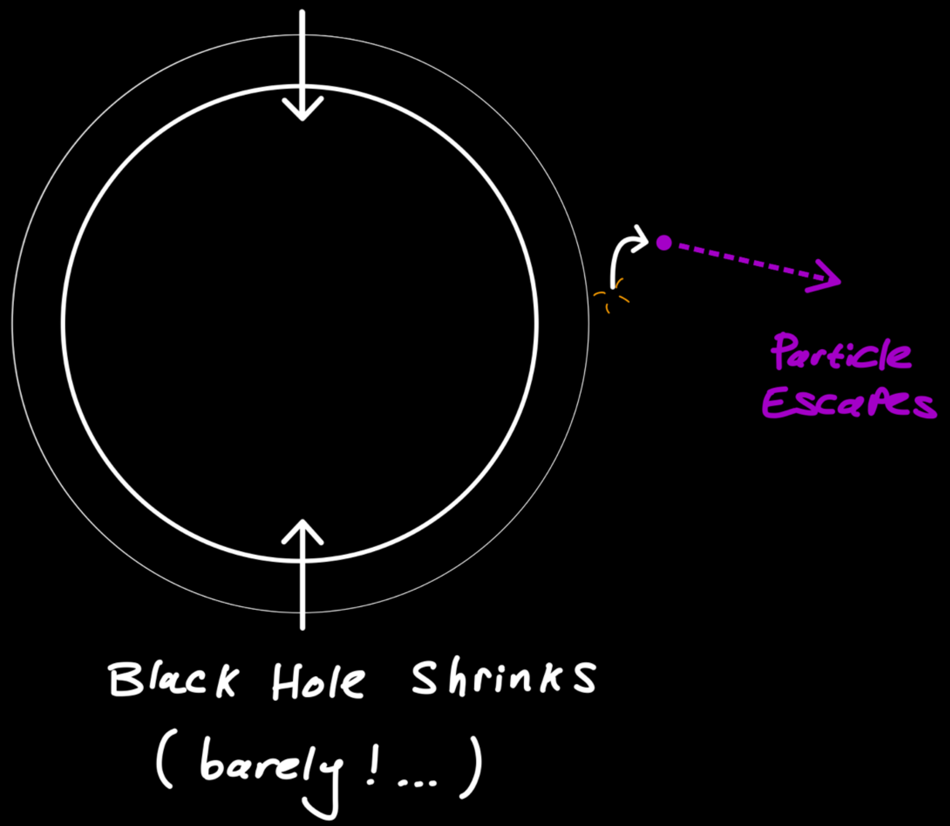


Hawking Radiation

The black hole cheats nature, and prevents the particles from annihilating and dissolving back into the vacuum.

But nature cannot be fooled… The escaping particle, who's mas was borrowed from the vacuum carries a debt that must be paid.

The Black Hole pays this debt, and reduced in mass by a miniscule amount (equal to the mass of the escaping particle).



Questions!

Spacetime Sundays

Southend's First Science Community Drop-in:

part office-hour, part lecture, part book club

Approximately every other Sunday 11am-12pm in the Beecroft Gallery Foyer

Upcoming dates:

28/06

19/07

02/08

Join the Mailing List for Updates!

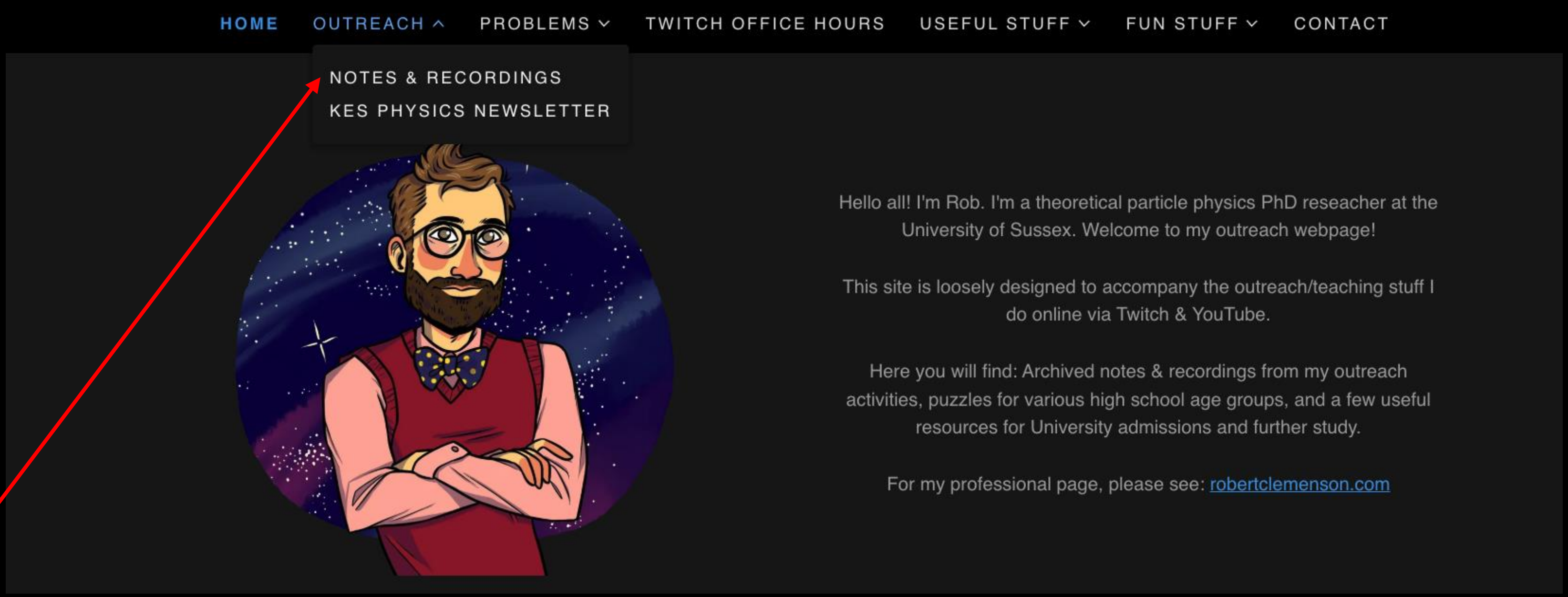
Visit:

Spacetime-Sundays.com

Lecture Slides

These lecture slides are available on my outreach website:

CosmicConundra.com



Coming Up…

The Science of Spacetime: A Physicists Guide to the Galaxy

Every other Saturday 11:30am in the Beecroft Gallery Lecture Theatre

~~Building a Universe from Scratch (06/06)~~

~~Black Holes: Monsters of the Cosmos (20/06)~~

The Physics of Science Fiction: Tardises, Teleports, and beyond… (04/07)

“Not Even Wrong”: The Strangest Ideas in Theoretical Physics (18/07)