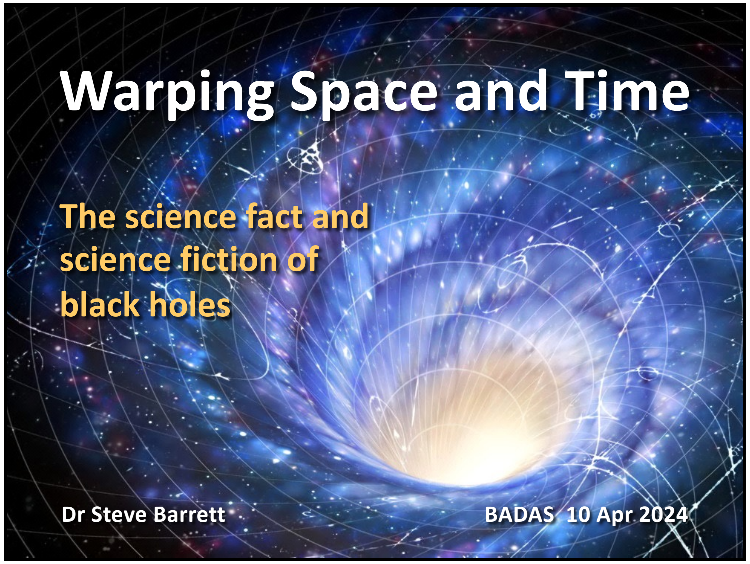


Contents

UNIVERSITY OF LIVERPOOL 2

A Brief History

Black Hole [definition]:

A region of space from which nothing, not even light, can escape.

When did the concept of a black hole originate? Earlier than you think.

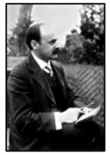
Rev John Michell (1783) – "If [the size of] a sphere of the same density of the Sun were to exceed that of the Sun in the proportion of 500 to 1 … all light emitted from such a body would be made to return towards it by its gravity."

In the 1800s the idea of such '**dark stars**' was largely ignored.

UNIVERSITY OF LIVERPOOL 3

A Brief History

Einstein (1915)
General Theory of Relativity



Schwarzschild (1916)
Calculation of gravity of a compact mass

Eddington (1926)
Stars compressed to the 'Schwarzschild radius'

Chandrasekhar (1931)
Massive stars at the end of their lives will collapse

Oppenheimer (1939)
Nothing can stop the collapse of massive stars

General Relativity predicts that time stops at the Schwarzschild radius and so such collapsed stars were called '**frozen stars**'.

UNIVERSITY OF LIVERPOOL 4

A Brief History

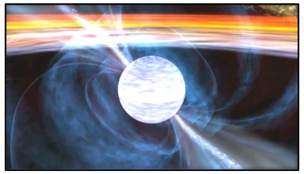
Finkelstein (1958)
At the Schwarzschild radius there is an event horizon – a 'one-way membrane'

Golden Age of GR and BH (~ 1960 – 1975)
Kerr / Newman / Penrose / Hawking

1964 First use of the term '**black hole**'

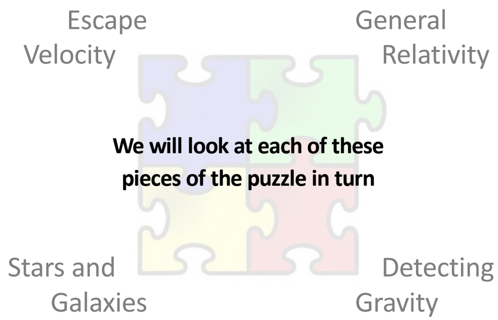
1967 Discovery of pulsars

1969 Identified as neutron stars

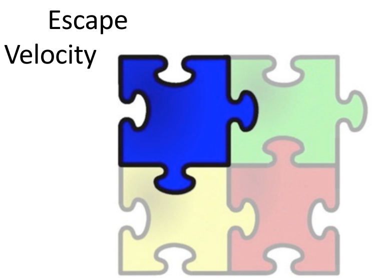


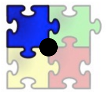
Gravitational collapse of stars is not just a hypothetical possibility!

Pieces of the Puzzle



We will look at each of these pieces of the puzzle in turn





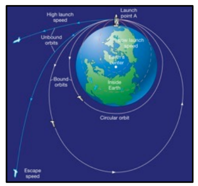
Escape Velocity

What goes up must come down? Right?

Wrong, not if it goes up fast enough.

The threshold speed needed for an object to escape the gravitational pull of a body is called the escape velocity. If you throw something up with a speed less than the escape velocity then it will fall back.

The force of gravity pulling an object (like you) towards a body (like the Earth) depends on both of the masses involved and the distance between them. The escape velocity does not depend on the mass of the object — the escape velocity for a 1 kg satellite is the same as for a 1 ton satellite or even a 1000 ton space station.



Escape Velocity

The escape velocity at the surface of a body depends on the ratio of the mass to the radius

$$\frac{M}{R}$$

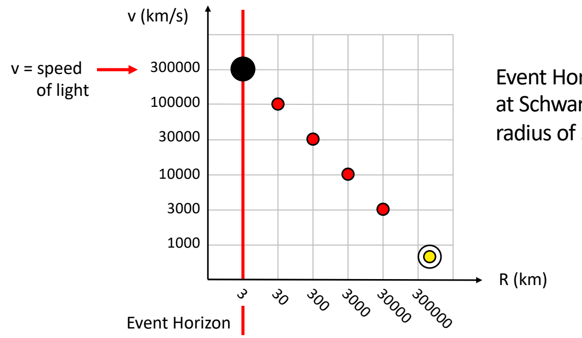
Some escape velocities:

Velocity to escape the Moon	= 2 km/s	(=	5,000 mph)
Velocity to escape the Earth	= 11 km/s	(=	25,000 mph)
Velocity to escape the Sun	= 600 km/s	(>	1,000,000 mph)

600 km/s may sound like a lot, but it is only 0.2% of the speed of light

Escape Velocity

Let's compress the Sun to smaller sizes and see what happens to the escape velocity.



Event Horizon at Schwarzschild radius of 3 km

Escape Velocity

If we compress the Sun into a sphere of radius 3 km then we form a black hole.

What if we start with a body with a different mass?

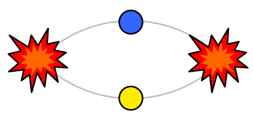
For the Earth the Schwarzschild radius is	~ cm	
Moon	~ 0.1 mm	
Mt Everest	~ atom	

We know of no way that this can happen for any mass smaller than that of a star, but that doesn't mean that it's impossible.

Escape Velocity

Although all sizes are possible, small BH don't last.

Aside: Quantum Mechanics* allows particles and antiparticles to be created from borrowed energy, as long as they annihilate and pay back the borrowed energy on very short time scales.

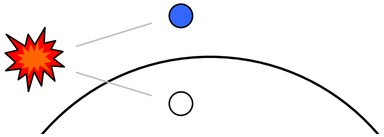


* See "The Weird World of the Very Very Small"

Escape Velocity

Although all sizes are possible, small BH don't last.

How is this particle-antiparticle creation relevant to the lifetime of BH? What might happen if they are created *just* outside the event horizon?

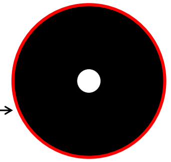


There is a net flux of particles radiating from the event horizon of the BH called Hawking radiation. This radiation increases with decreasing mass, so small BH evaporate! More about this later in the talk.

Escape Velocity

What happens if we compress an object to a size *smaller* than the Schwarzschild radius?

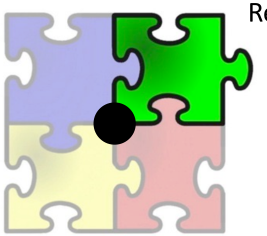
The event horizon, the point at which the escape velocity is equal to the speed of light, is still the same (the Schwarzschild radius).



For massive stars ($M > 10M_{\odot}$) nothing that we know of can stop the core collapse during a supernova and so all the mass is compressed to an infinitely small point – a singularity.

We cannot tell if this is what actually happens inside a BH because it is all hidden inside the event horizon. Could we ever see a "naked" singularity? Not according to the Cosmic Censorship Hypothesis.

General Relativity

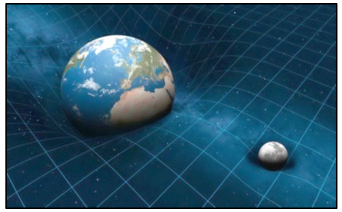


General Relativity

Einstein's General Theory of Relativity
First presented in 1915 and published in 1916

What does it say? $G = 8\pi T$

The main principle of GR can be expressed by this one equation that looks deceptively simple.



G is the geometry of space
T is the distribution of mass

Mass distorts space!

General Relativity

$$G = 8\pi T$$

The equation is sometimes reduced to the more prosaic description

Mass tells **space** how to **curve**

Space tells **mass** how to **move**

What do we mean by curved space?

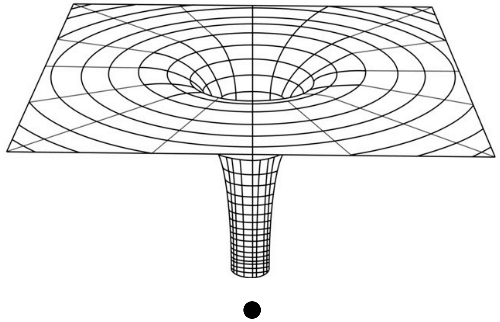
Any image trying to explain this uses the analogy of 2-dimensional space curving into a third dimension.

To warp or curve 3-dimensional space we need a fourth dimension which humans, not unnaturally, find very difficult to imagine.

UNIVERSITY OF LIVERPOOL 17

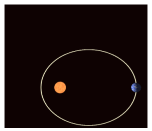
General Relativity

Black holes produce infinitely warped space

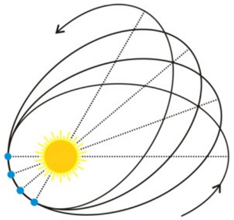


UNIVERSITY OF LIVERPOOL 18

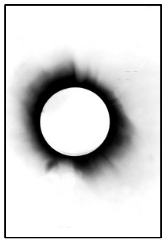
Predictions of General Relativity



The precession of the orbit of Mercury



Gravitational lensing



Stars seen during the total solar eclipse of 1919 were found to be slightly shifted in position.

UNIVERSITY OF LIVERPOOL 19

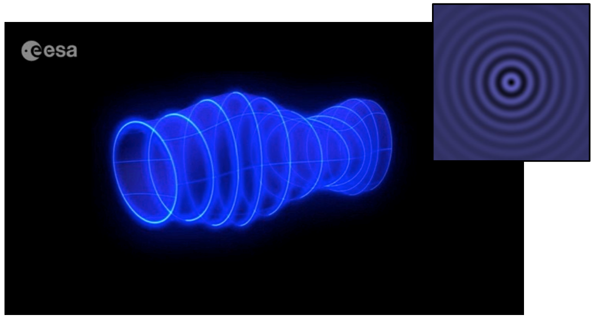
Predictions of General Relativity

Time slows down in a gravitational field

UNIVERSITY OF LIVERPOOL 20

Gravitational Waves

One of the predictions of GR is gravitational waves.



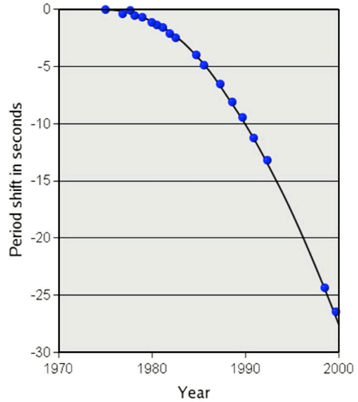
The ripples in spacetime are tiny — 1 part in 10^{20}

UNIVERSITY OF LIVERPOOL 21

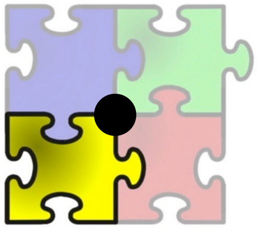
Gravitational Waves

If binary pulsars emit gravitational waves they must be slowly losing energy, and this would mean that they would be expected to slow down (black line).

This is precisely what is observed (blue points).



UNIVERSITY OF LIVERPOOL 22



Stars and Galaxies

UNIVERSITY OF LIVERPOOL 23

Black Holes Are Born

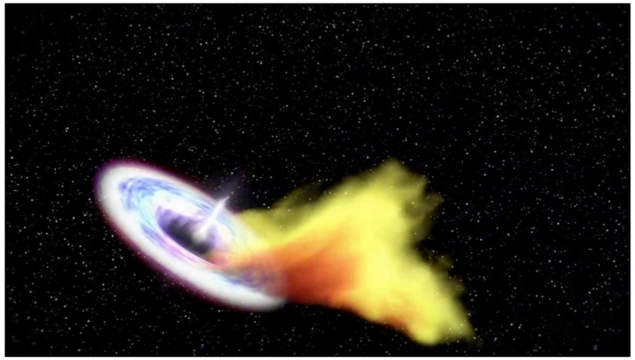
Core collapse of a massive star – Supernova*

UNIVERSITY OF LIVERPOOL

* See "The ABC of Stellar Evolution" 24

Black Holes Feed

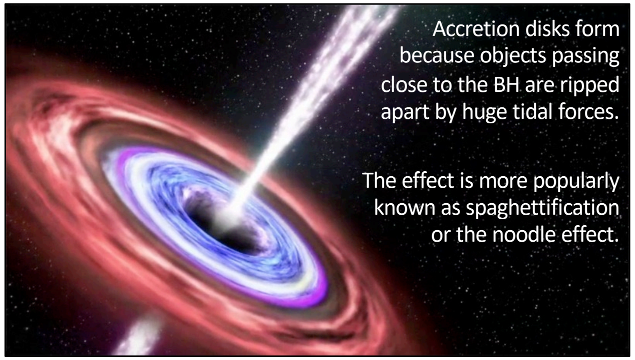
Infalling matter forms an accretion disk



UNIVERSITY OF LIVERPOOL

Black Holes Feed

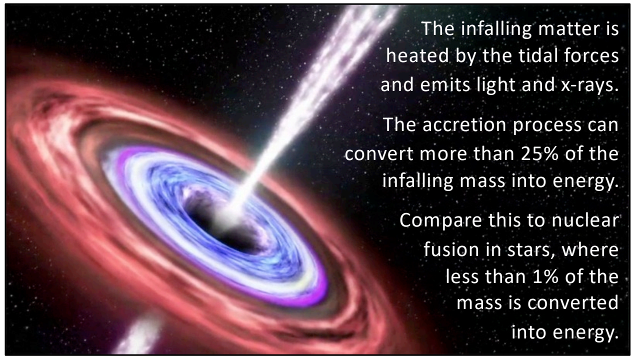
Accretion disk and x-ray jets



UNIVERSITY OF LIVERPOOL

Black Holes Feed

Accretion disk and x-ray jets



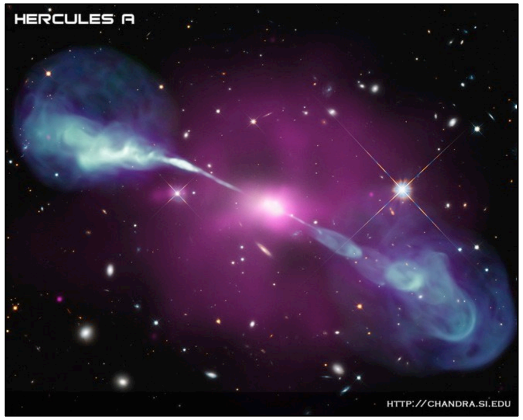
UNIVERSITY OF LIVERPOOL

Black Holes Feed

Is this how black holes feed on neighbouring stars?

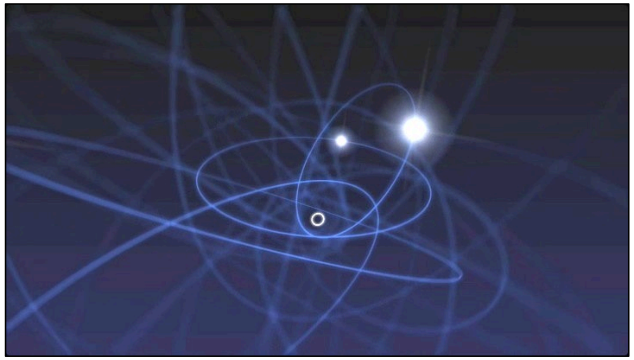
UNIVERSITY OF LIVERPOOL

Black Hole Jets



Supermassive Black Holes

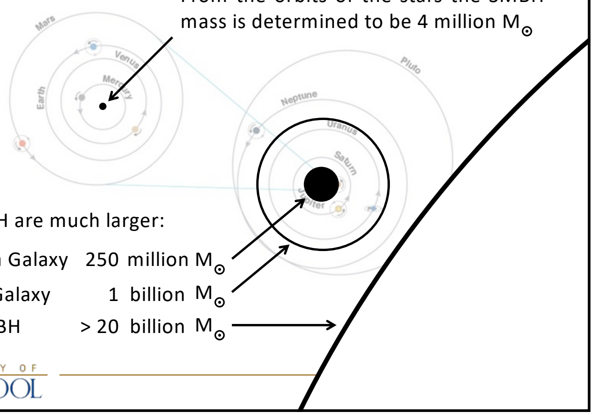
Stars orbiting the BH at the centre of the Milky Way



Supermassive Black Holes

How big is the SMBH at the centre of the Milky Way?

From the orbits of the stars the SMBH mass is determined to be 4 million $M_\odot$



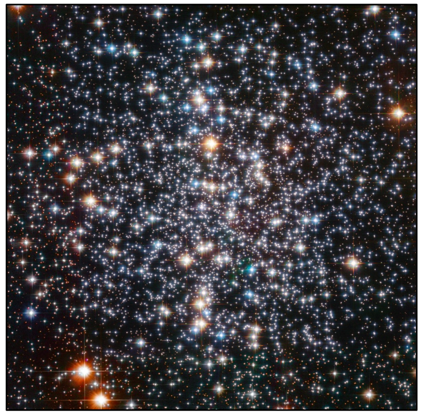
Other SMBH are much larger:

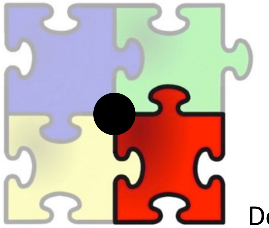
Andromeda Galaxy	250 million $M_\odot$
Sombrero Galaxy	1 billion $M_\odot$
Largest SMBH	> 20 billion $M_\odot$

Black Hole In Star Cluster

Using the same technique, the Hubble Space Telescope has detected a massive black hole at the core of this star cluster.

Do all large clusters contain a black hole?



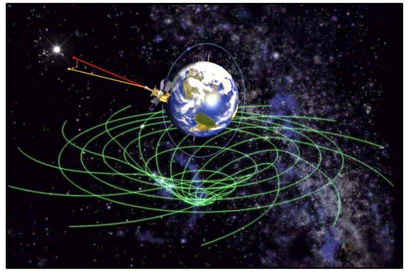


Detecting Gravity

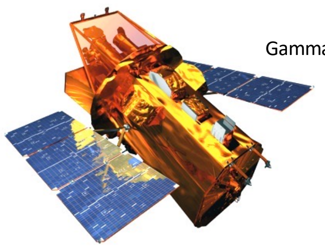
Measuring Curved Space

Gravity Probe B

2004



Detecting Extreme Gravity



SWIFT

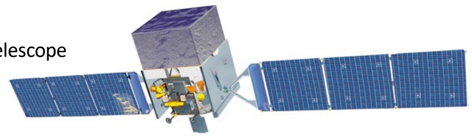
Gamma-Ray Burst Mission

2004

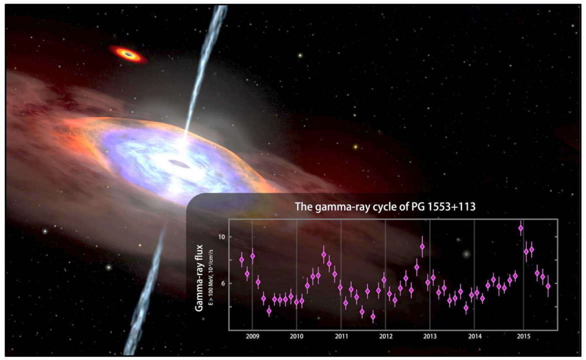
FERMI

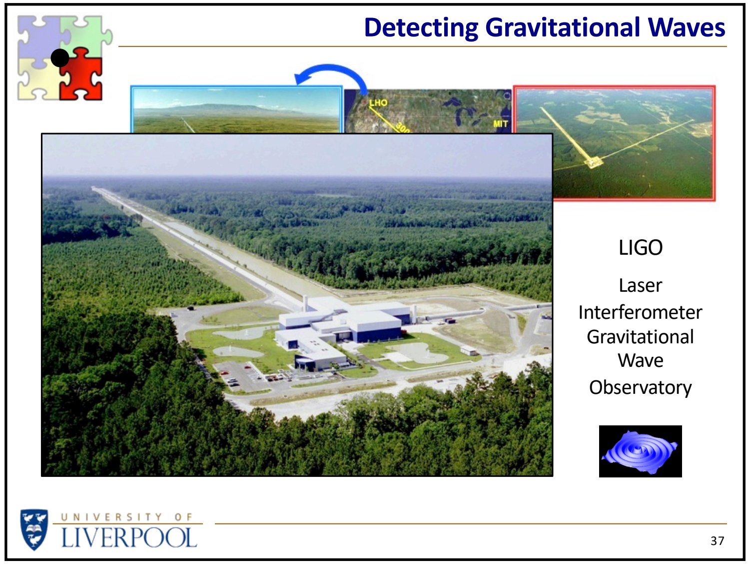
Gamma-Ray Space Telescope

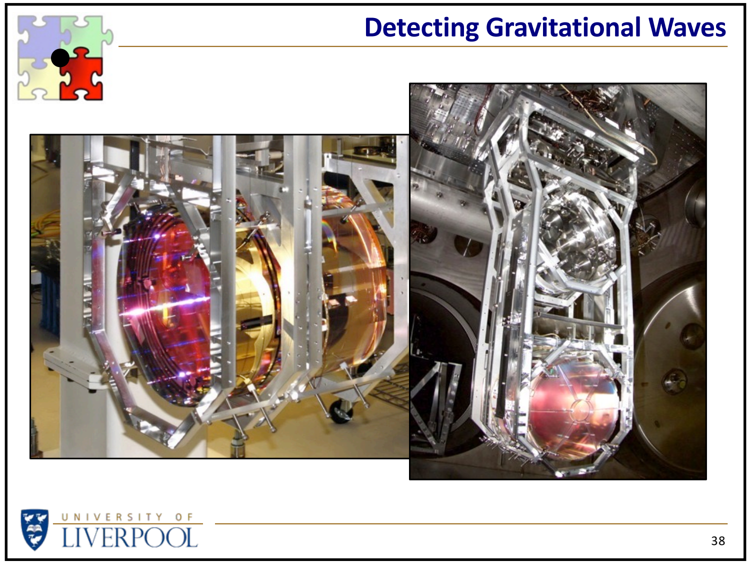
2008

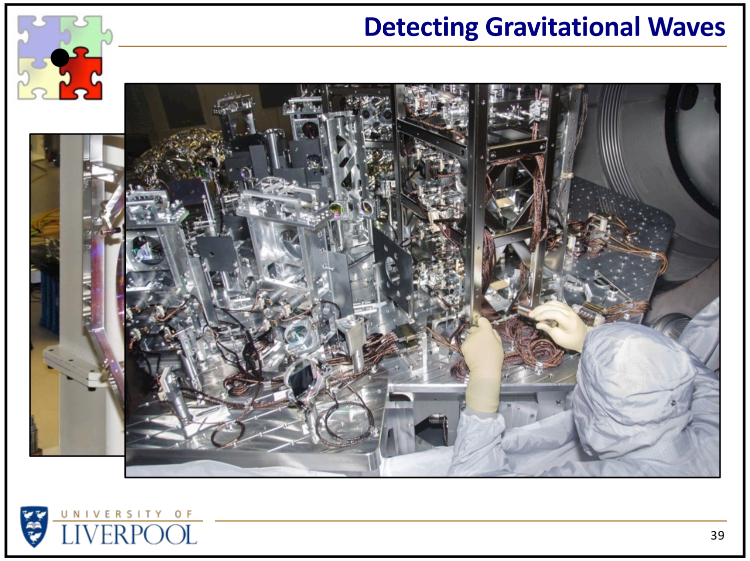


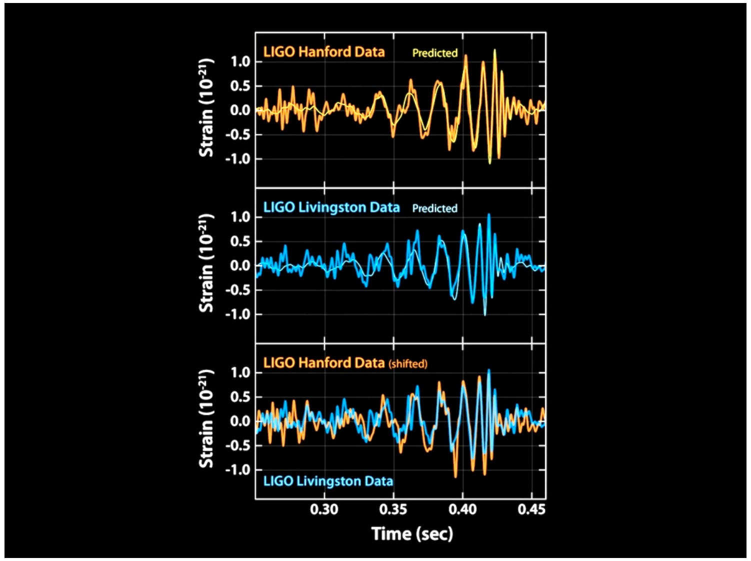
Detecting Extreme Gravity




Detecting Gravitational Waves
LHO
MIT
LIGO
Laser
Interferometer
Gravitational
Wave
Observatory
UNIVERSITY OF
LIVERPOOL
37

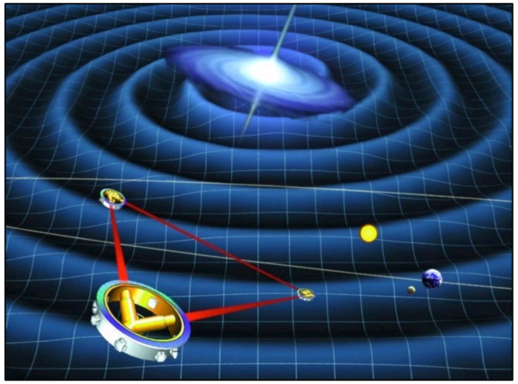

Detecting Gravitational Waves
UNIVERSITY OF
LIVERPOOL
38


Detecting Gravitational Waves
UNIVERSITY OF
LIVERPOOL
39


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

Detecting Gravitational Waves

eLISA = Evolved Laser Interferometer Space Antenna



UNIVERSITY OF LIVERPOOL 41

Detecting Gravitational Waves

eLISA = Evolved Laser Interferometer Space Antenna

LIGO is sensitive to waves with periods of less than a second. This means that it can detect waves created by the merger of two black holes, but this does not happen very often.

By comparison, eLISA will be sensitive to waves with much longer periods, from seconds to hours. This should mean that eLISA can detect signals from BH within our galaxy and SMBH in other galaxies.

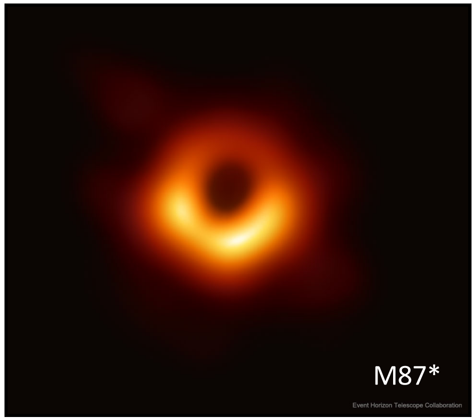
It is also hoped that eLISA will be able to detect the gravitational waves created by the biggest singularity of them all – the Big Bang.*

UNIVERSITY OF LIVERPOOL

* See "The Beginning of Everything"

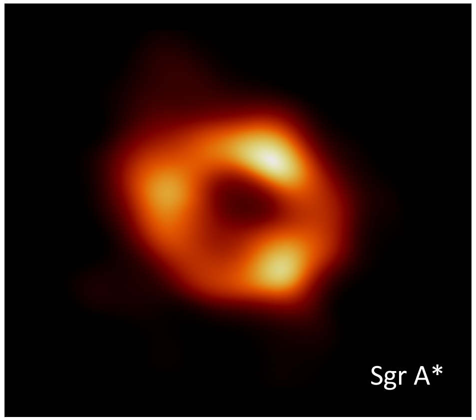
42

Event Horizon Telescope



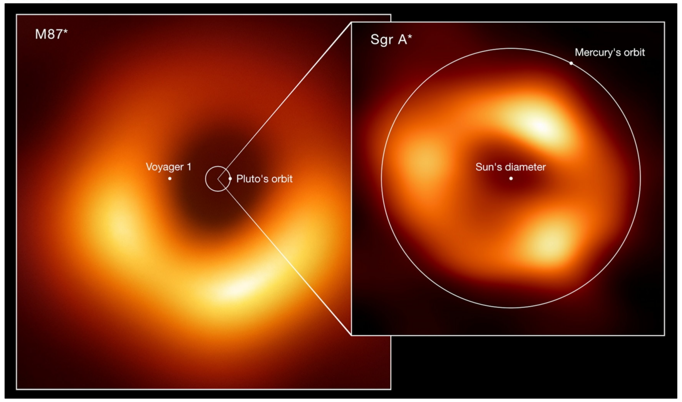
UNIVERSITY OF LIVERPOOL 43

Event Horizon Telescope



UNIVERSITY OF LIVERPOOL 44

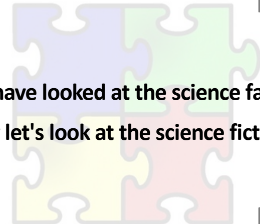
Event Horizon Telescope



Pieces of the Puzzle

Escape Velocity

General Relativity



We have looked at the science facts

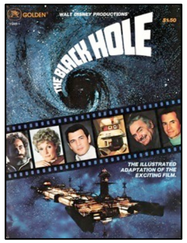
Now let's look at the science fiction

Stars and Galaxies

Detecting Gravity

Science Fiction

Does Hollywood ever get it right?



Ship is parked right next to the event horizon

Ship is pulled in to a planetary black hole

Ship is powered by an onboard black hole

Science Fiction

Is a BH-powered star drive possible?

For BH with mass less than a kg, not much energy is available ($E = mc^2$).

For BH with a mass more than that of Mount Everest, Hawking radiation is very weak.

For BH with mass ~1 million tons the power in the Hawking radiation would be equivalent to the output of ~100 million nuclear power stations and the BH would last ~100 years.

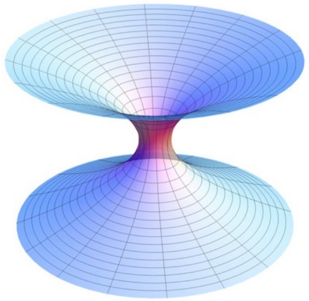
If the radiation from such a BH, smaller than an atom, could be captured or directed, then that is enough energy to power a starship.

Science Fiction

What about shortcuts through space?

Wormholes?

Hyperspace?



UNIVERSITY OF LIVERPOOL

49

Science Fiction

What about shortcuts through space?

Wormholes?

Hyperspace?

UNIVERSITY OF LIVERPOOL

50

Science Fiction

What about time travel?

UNIVERSITY OF LIVERPOOL

51

Science Fiction

What about time travel?

Hawking proposed the

Chronology Protection Conjecture

A wormhole allowing time travel will collapse before anything has time to travel through it.

"Making the Universe safe for historians"

UNIVERSITY OF LIVERPOOL

52

The Problem

There's a problem.

General Relativity (GR) works really well for massive objects (like stars).

Quantum Mechanics (QM) works really well for tiny objects (like atoms).*

But, what if the object is massive **and** tiny?

Then we need (drum roll)... Quantum Gravity.

The problem: GR and QM are not good bedfellows.

A universal 'Theory of Everything' has proven to be elusive.

UNIVERSITY OF LIVERPOOL

* See "The Weird World of the Very Very Small"

53

The Future

Maybe quantum mechanics will prevent a singularity from forming, thus avoiding the horrible properties like infinite density and infinitely warped space.

For instance, String Theory describes a ten-dimensional universe in which the fundamental building blocks are 'strings' rather than the more familiar 'particles'.

If String Theory is right, black holes are 'fuzzballs' without a singularity at their core. They are just 'balls of string'.

But, is the universe described by String Theory the one in which we live?

UNIVERSITY OF LIVERPOOL

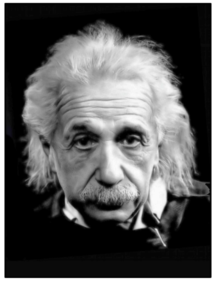
54

The Future

Einstein never really believed that quantum mechanics was the right description of the microscopic world.

He spent most of his later years wrestling with a Theory of Everything.

If a genius like Einstein could not get his head around the problem, what will it take?



Maybe some unexpected discoveries, for instance from LIGO or eLISA, will point the way forward to a better understanding of black holes.

UNIVERSITY OF LIVERPOOL

55