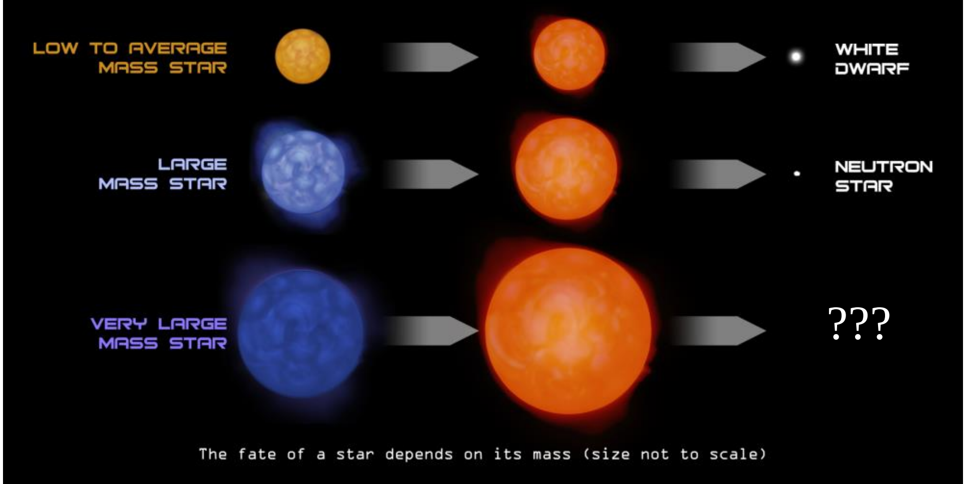
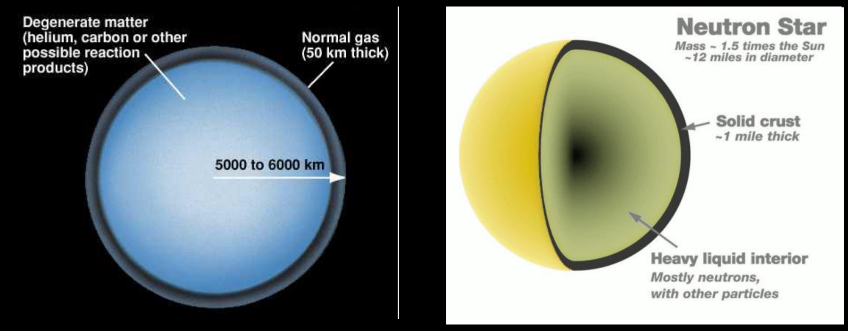
Upcoming Astronomy-themed Talks and Events

Tuesday, 2/18, 12-1pm Astro Lunch – Phys-Astr B305 – Jessica Werk, (UW) – “Experiments to build off accurate distances to molecular/dust clouds”.

Thursday, 2/20, 3:45-5:00p Astronomy Colloquium – Phys-Astr A102 – Anthony Pullen (NYU) – “Line Intensity Mapping: Modeling & Analysis in the Precision Era”.



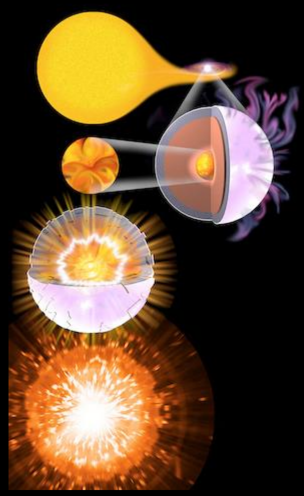
We saw last time how the mass of a star determines what sort of ‘corpse’ it leaves behind once fusion has ceased in its core.



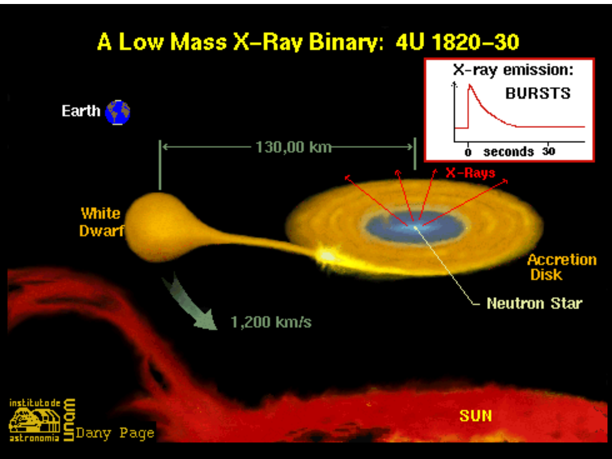
Schematics of a White Dwarf and a Neutron Star (Note: Sizes not to scale!)

Since they generate no fusion energy, White Dwarfs and Neutron Stars fend off gravity via 'degeneracy pressure' – from tightly packed, relativistic electrons in the case of a White Dwarf, and from neutrons in the case of a Neutron Star.

This image is a bit better to scale – recall that White Dwarfs are about the size of the Earth, while Neutron Stars are much smaller, about the size of a city. Yet they are more massive than White Dwarfs, and the gravitational forces near their surfaces are much, much stronger – Vancouver would not survive this encounter!

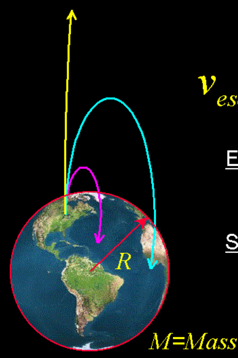


White Dwarfs ***can*** eventually do some more fusing – but only if they are in a binary system and gravitationally ‘cannibalize’ hydrogen from their companion. This fusion can take the form of a relatively (!) small, surface-level eruption called a “nova” – but if enough mass is transferred to get above the Chandrasekhar Limit of about 1.4 times the mass of the Sun one can get a “White Dwarf Supernova”.



Accretion onto Neutron Stars can also produce ‘nova’-like phenomenon as material fuses on their surfaces – but what happens if so much material accretes onto the Neutron Star that its self-gravity exceeds the strength of its neutron degeneracy pressure? What becomes of a Neutron Star if it begins to collapse yet again?

Certainly the gravitational forces would increase – and remember the surface gravity of a neutron star is 10^{11} times that of the Earth already, with escape velocities approaching 200,000 km/s! It would only need to shrink by a factor of a few before its escape velocity exceeded the speed of light itself – if it could get that small, you wouldn't be able to see it!



$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

Earth:
v_{esc} = 11 km/sec
(24,600 mph)

Sun:
v_{esc} = 615 km/sec
(1.4 Million mph)

For a $2.9M_{Sol}$ neutron star with a 10km radius, v_{esc} ~ 275,000 km/s!

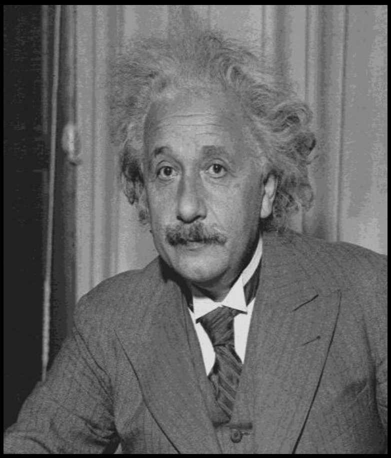
Such a "dark star" was postulated as early as 1783 by John Michell and Pierre Simon-Laplace, who simply equated the Newtonian escape velocity with the speed of light to derive the relationship between the mass and size of such an object.

$$v_{esc} = c = \sqrt{2GM / R}$$

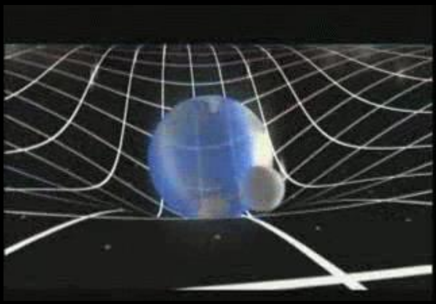
$$R_{DarkStar} = 2GM / c^2 \approx 3(M / M_{Sol})\text{km}$$

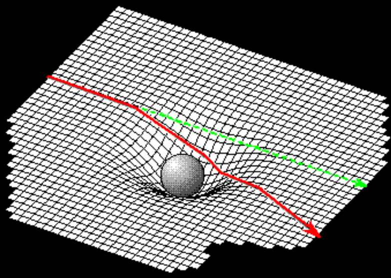
For a star like the Sun, this led to what was at the time believed to be unrealistically small values. Further, most physicists had begun to think of light as waves (rather than particles), and did not think that gravity could affect such waves directly.

After all, light has no mass, so how could gravity affect it? Einstein's General and Special Theories of Relativity revealed that gravity is really a distortion of spacetime, ***caused*** by objects with mass. Because light – like everything else in our universe – moves through spacetime, this means that light is affected by gravity – even though photons themselves have no mass.

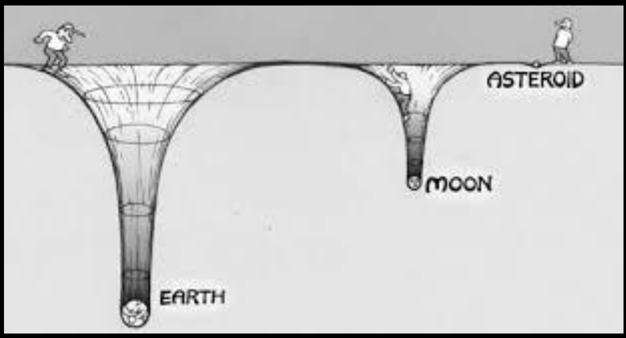


According to relativity, gravity warps spacetime in a manner analogous to the way a person standing on a trampoline distorts the surface of the trampoline. The person makes a "pit" on the rubber sheet that affects the motion of other objects on the trampoline.

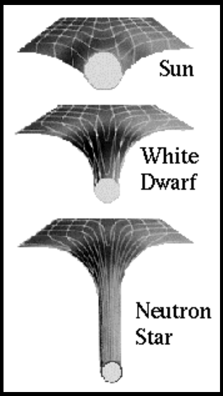


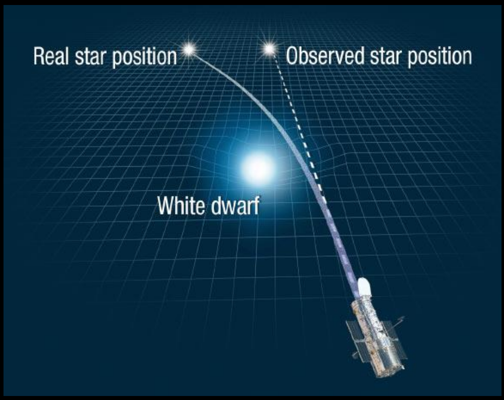


The curvature causes massive objects to orbit each other, for example, and can even cause the path of light – forced to move on the surface of the spacetime "trampoline" – to bend as well.

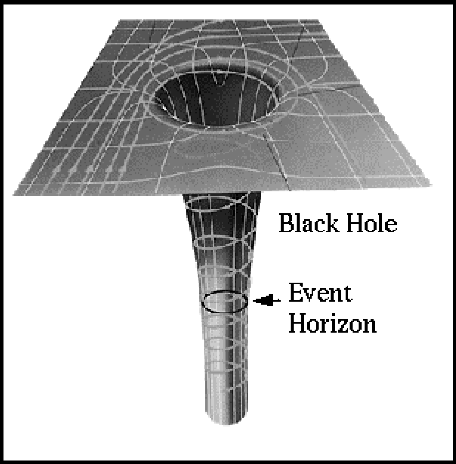


More massive objects make deeper, more severe distortions in spacetime – and we often refer to these distortions as 'gravitational wells'. The Earth's gravitational well is much deeper than the Moon's, but much less deep than that of the Sun.

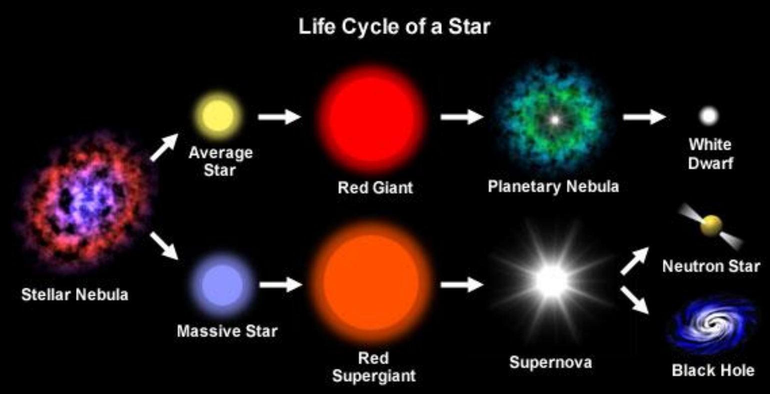




Because their mass is packed into an even smaller area of space, White Dwarfs and Neutron Stars produce even deeper gravitational wells, and the effects they cause on light can be (and have been!) clearly observed, confirming our models of relativity to a very high degree of accuracy and precision.



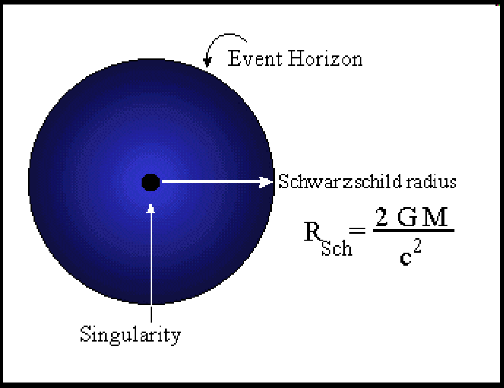
But relativity suggests these distortions can go *much* farther for even denser objects. In fact, close to a steep enough gravitational well, the path of light can become so warped that it is effectively trapped inside the well. And since no light can escape from within that region, no “events” that occur there – inside the “event horizon” – could ever be observed from points outside.



We call any object that can produce such an event horizon a ***black hole*** – and we believe that one way nature can in fact make such an object is through the collapse of a neutron star, during or after the death of a high-mass star.

Any neutron star above ~ 2.9 M_{Sol} should collapse completely and without limit, on timescales of less than 10^{-6}s, in theory becoming <u>infinitely</u> small. This creates an incredibly strong gravitational field near its center that warps spacetime sufficiently that light is indeed prevented from escaping – Michel and LaPlace's idea reborn by relativity!

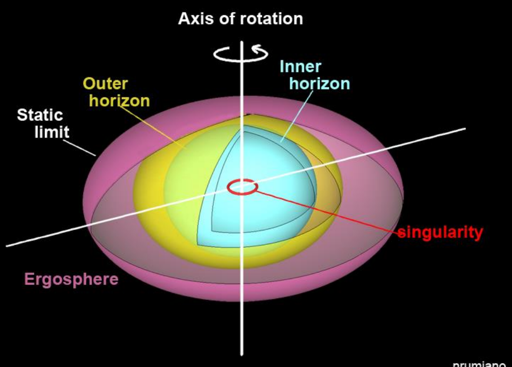
Animation of the formation of a black hole during a "High-Mass Star Supernova".

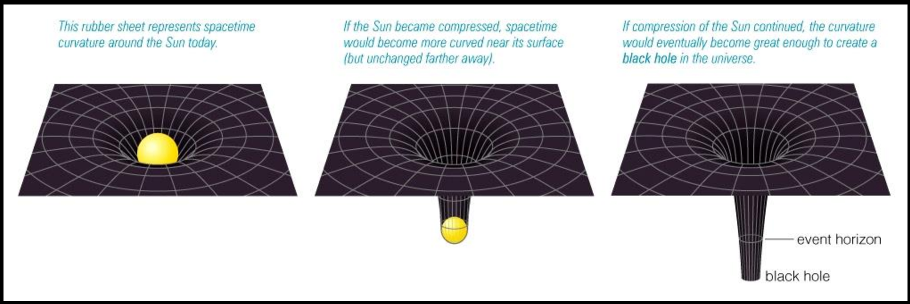


And for a non-rotating black hole, the event horizon lies precisely where their naïve Newtonian derivation would suggest, at the so-called ***Schwarzschild Radius***. All of the mass, however, is located at the ***singularity*** at the black hole's center – so that there is no mass or other material at the event horizon itself (but stay tuned on that!).

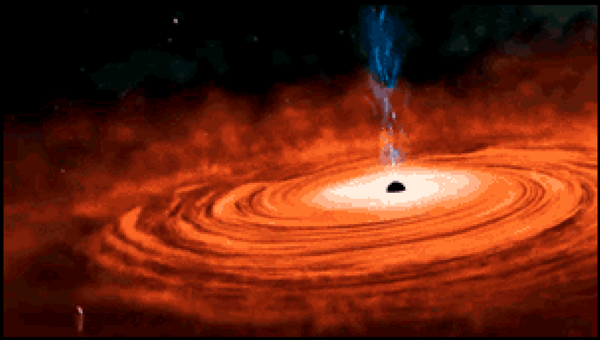
The geometry is a bit more complicated for the interior of a ***rotating*** black hole – including multiple 'event horizons' and a ring-shaped singularity.

Baffling and difficult to observationally constrain? You bet! The interiors of black holes contain many unsolved mysteries!

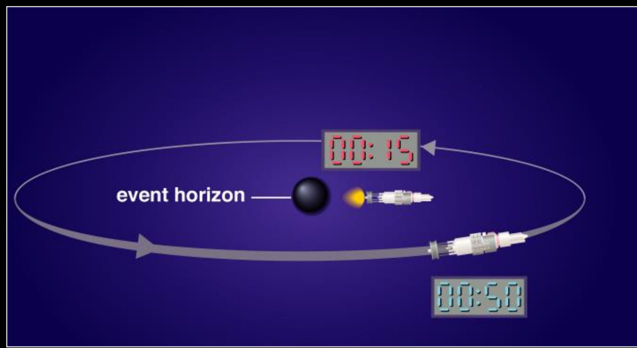




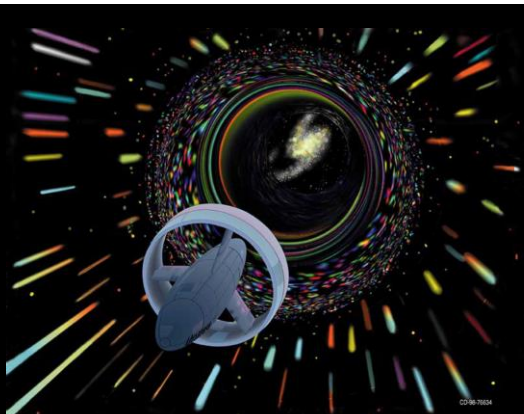
But at a sufficient distance, a black hole exerts gravitational force according to Newton's Law, just like any other star with the same mass. If, for example, our Sun was replaced by a one solar mass black hole, the orbits of the planets would not change!



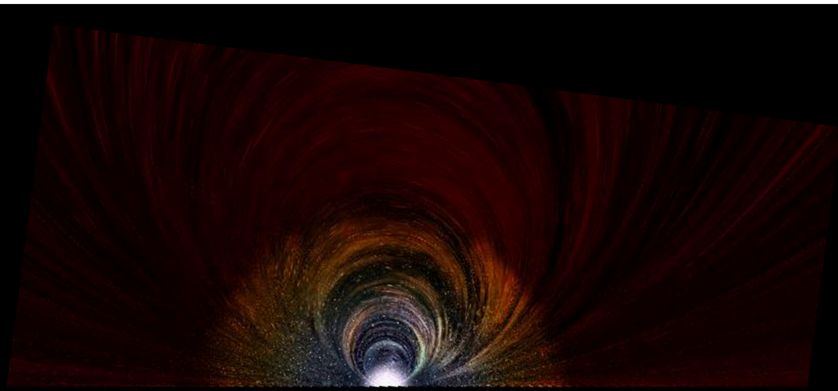
For a non-rotating black hole, you must be within ~ 3 times the Schwarzschild radius from the black hole before gravity deviates from what Newton's Law predicts (that's within 6 miles, for a 1 solar mass black hole!). Only then would an otherwise stable orbit eventually spiral into the black hole.



In the close vicinity of the black hole, however, there are some strange effects – time, for example, slows down. If we launched a probe into a black hole, as it approached the event horizon time would appear to slow for the probe, as seen from an outside observer – e.g., it might take 50 min of time on the mother ship for 15 min to elapse on a probe closer to the black hole.



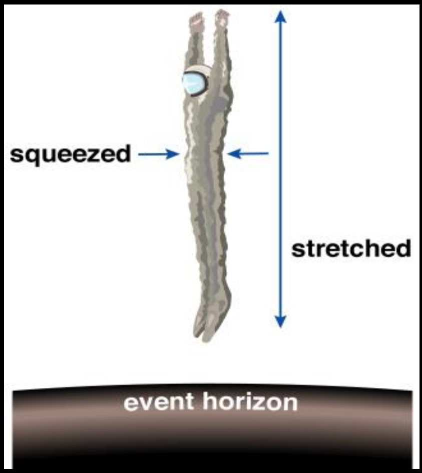
But note what this means – if the probe then returns to the mother ship, the mother ship will have experienced more time passing than the probe, which is another way of saying that the probe *traveled into the future* of the mother ship! Time travel using black holes is totally doable, you just need to get really close to the event horizon!



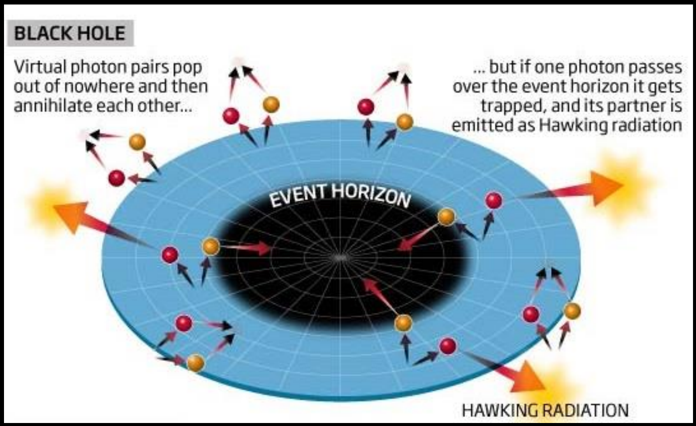
Panoramic view of an orbit at the ‘photon sphere’, event horizon below.

Light is also (and obviously!) strongly affected near a black hole – as the probe approaches the black hole, light from the outside universe becomes infinitely blueshifted and focused by the intense warping of the space near the black hole.

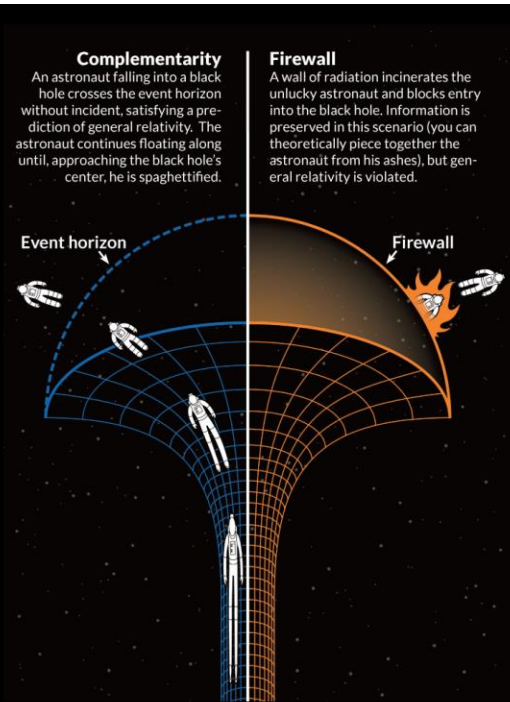
A ‘relatively’ realistic model of an approach to and through a charged black hole’s interior, courtesy A. Hamilton (UC Boulder)



But really, Tidal Forces would destroy a probe long before it could cross the Event Horizon – as our probe approaches, the difference between the gravitational force felt by our astronaut's feet becomes significantly stronger than that felt by our astronaut's head! Angular differences in the gravitational field are just as bad and squeeze the astronaut from the sides – so that any physical object would be "spaghettified".



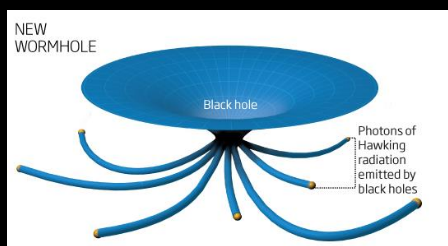
Or – perhaps burnt to a crisp! So-called "Hawking Radiation" is believed to be produced at the event horizon, and this can eventually lead to the 'evaporation' of the black hole as it steadily radiates away energy over time.

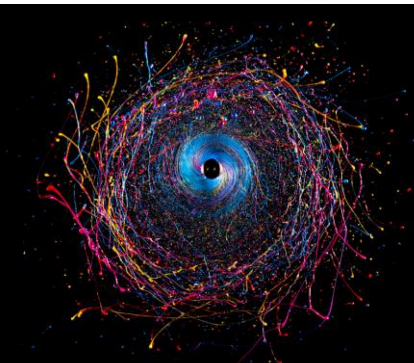


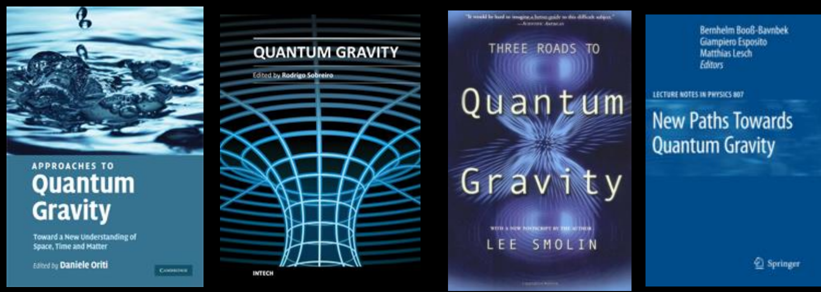
Many have suggested that this radiation forms a ‘firewall’ around the black hole – which would incinerate our astronaut instead of spaghettifying her!

Either way, it’s bad news for Matthew McConaughey and Anne Hathaway!

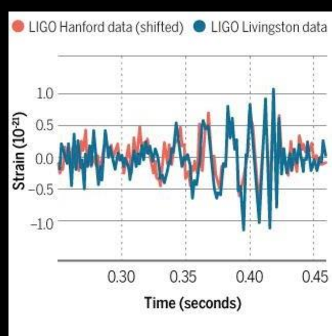
These ideas are at the cutting edge of studies of the physics of black holes – are black holes in fact ‘grey’? Do they contain ‘Planck’ stars, instead of infinitely small singularities? Or wormholes to every virtual particle they’ve ever created?



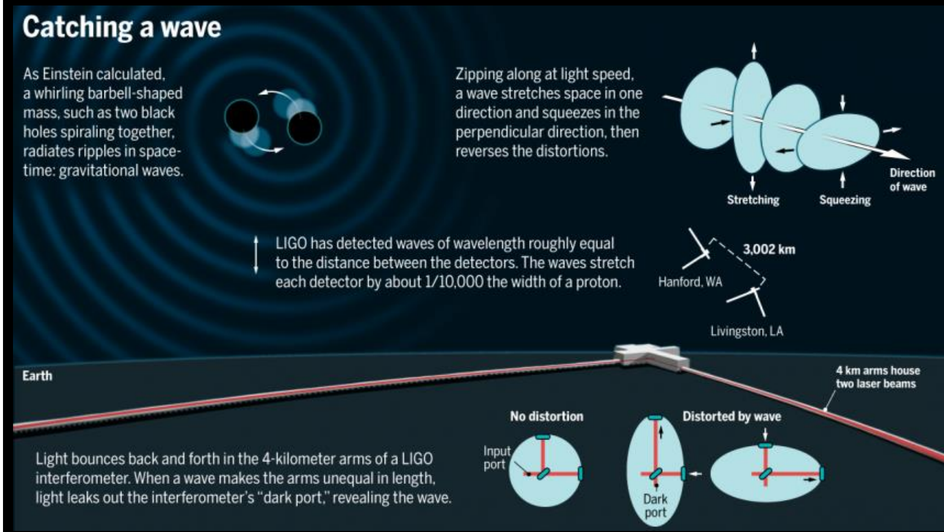


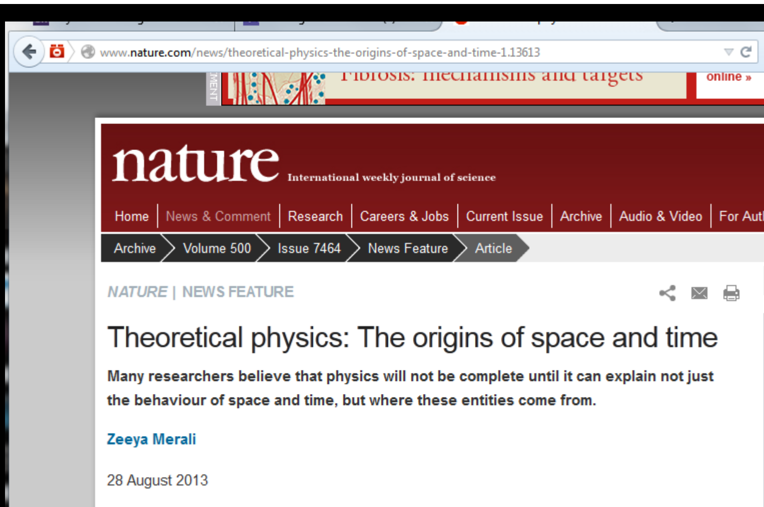


This uncertainty is deeply tied to our ideas about ***quantum gravity*** – a general term for theoretical attempts to reconcile quantum mechanics with general relativity – and one of the key reasons for all the excitement about the recent detection of gravitational waves from the mergers of black holes and neutron stars.



The animation above is based on white dwarfs merging, but the production of gravitational waves is the same with black holes and neutron stars – as they orbit, those waves carry away energy and the orbiting objects eventually merge, producing an ‘explosion’ of gravitational energy which we can detect.





www.nature.com/news/theoretical-physics-the-origins-of-space-and-time-1.13613

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NATURE | NEWS FEATURE

Theoretical physics: The origins of space and time

Many researchers believe that physics will not be complete until it can explain not just the behaviour of space and time, but where these entities come from.

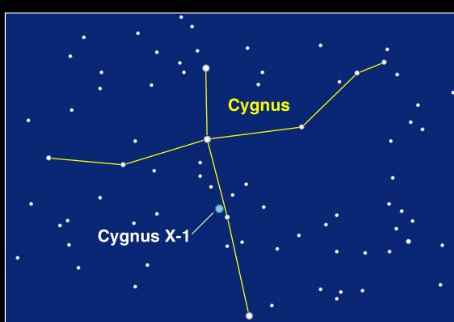
Zeeya Merali

28 August 2013

What does all this mean for quantum gravity? It's not very clear, but it does allow us a marvelous new way to test models of spacetime. For a good review of this stuff, check out the article above, the links it contains, and more recent citations to it!

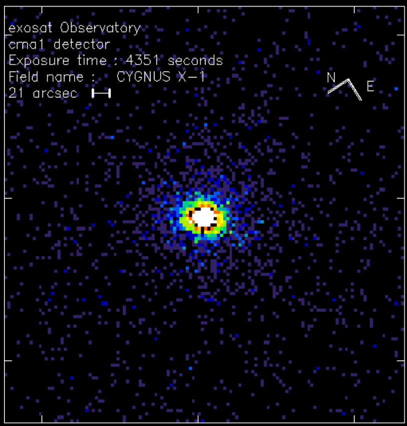
But gravitational wave measurements are very limited in the information they provide – most of our high resolution techniques involve light of some kind – so how can we study an object that doesn't emit any light? The key is to observe things *near* the black hole, operating under the influence of the black hole's gravity – for example, a black hole in a binary system.

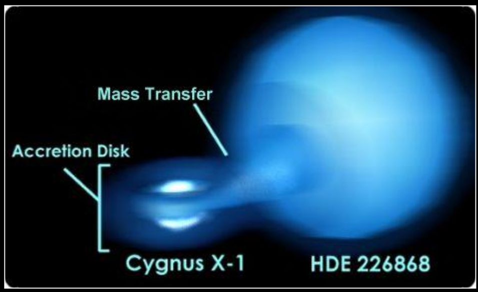
Cygnus X-1, a bright X-ray source first identified in the 1960's, is a system with a large, evolved giant star in orbit with an 'invisible' companion that emits copious X-rays.



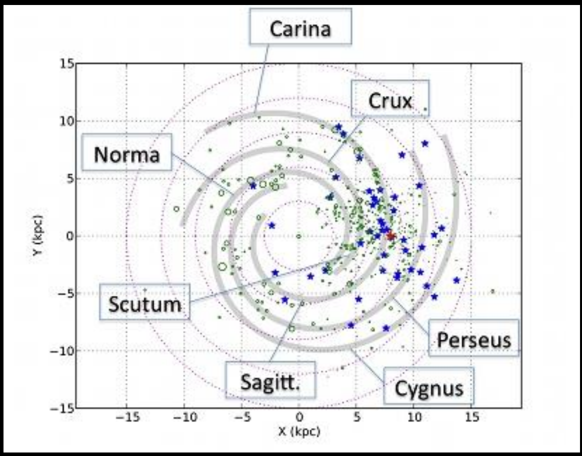
L – The location of Cygnus X-1; R – An optical image of the Cygnus X-1 system; the black hole is not one of the visible stars!

Observations of the bright star's motion give a mass ~ 10 $M_{\odot}$ for the unseen companion – which makes it too massive to be a neutron star. The only thing so massive, yet small enough to be otherwise invisible, is a black hole!





L – X-ray image of Cygnus X-1 – the bright source is the disk of material falling into the black hole; R – Artist's rendition of the Cygnus X-1 system.



As of today, many hundreds of such 'X-ray binary systems' are now known in our galaxy, and it seems clear that these puzzling monsters do indeed exist.

But that said, some of the most amazing and definitive evidence for the existence of black holes comes from a completely different – and historically unexpected – location that we'll explore next time!