PROPERTIES OF "REAL" BLACK HOLES, ACCORDING TO GENERAL RELATIVITY

HOMEWORK #5 ON WEBWORK – DUE AFTER FALL BREAK

TI EVALUATIONS

HALLOWEEN EXTRA CREDIT

PROPERTIES OF "REAL" BLACK HOLES ACCORDING TO GENERAL RELATIVITY

Formation of a black hole from the collapse of a massive, dead star

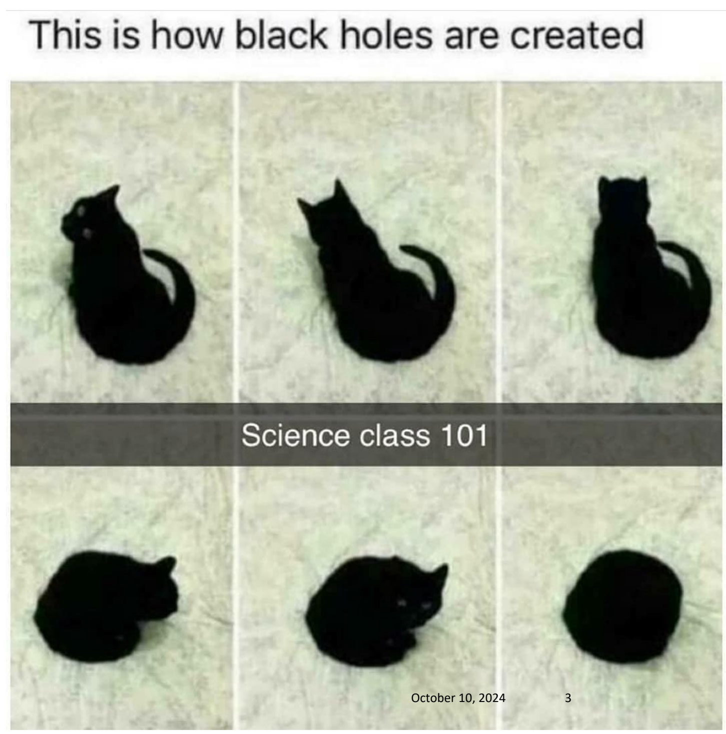
Properties of space-time near black holes

"Black holes have no hair."

"Space-time is stuck to the black hole."

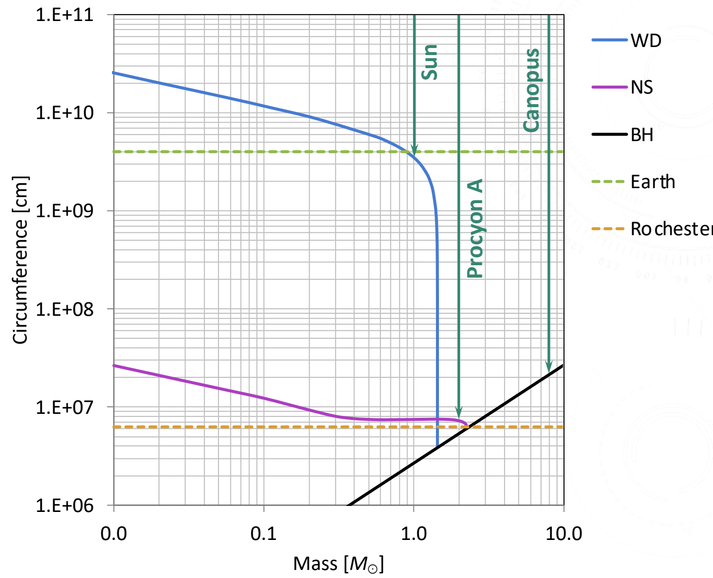
Spinning black holes

Black holes and gravitational radiation

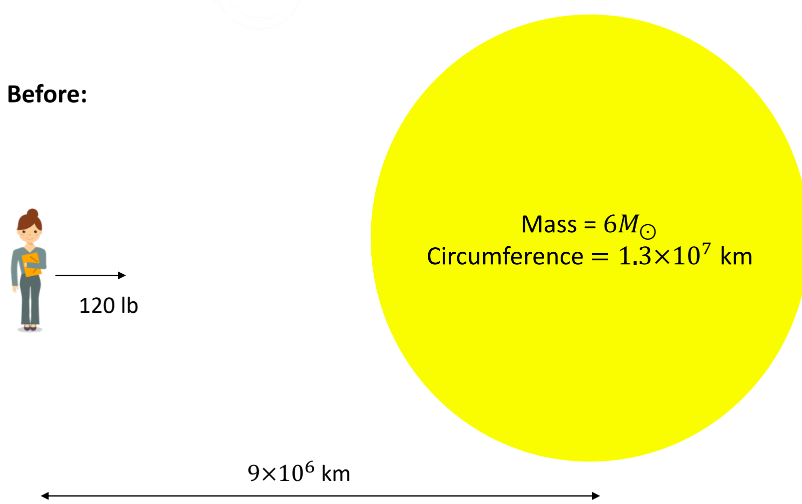


FINAL COLLAPSE OF BURNED-OUT STARS: WHITE DWARF, NEUTRON STAR, OR BLACK HOLE?

If these stars do not eject mass while in their death throes, their fates are as follows: the Sun will become a white dwarf, Procyon A would become a neutron star, and Canopus would become a black hole.



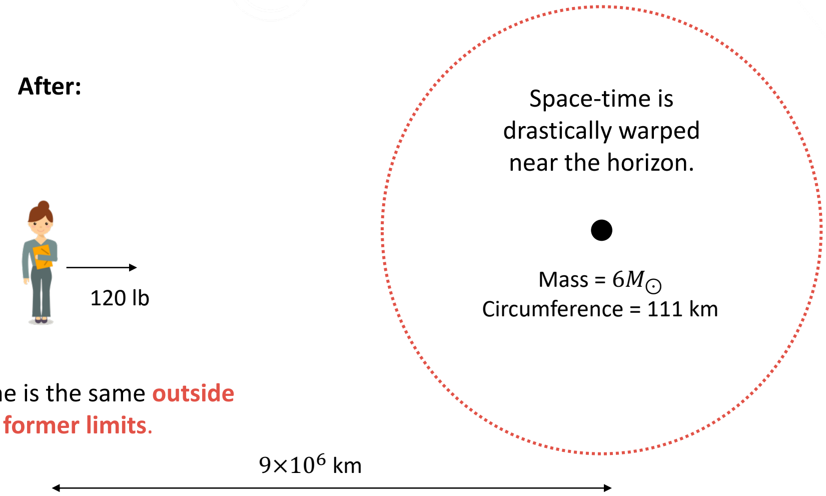
Before:



COLLAPSE OF A STAR TO FORM A BLACK HOLE

Same star from which we made a neutron star and a supernova.

After:



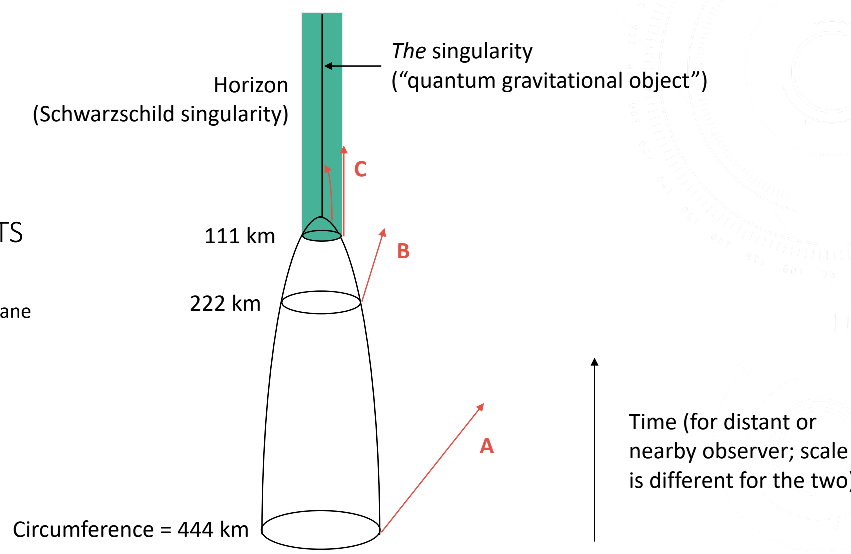
Space-time is the same **outside the star's former limits.**

COLLAPSE OF A STAR TO FORM A BLACK HOLE

Same star from which we made a neutron star and a supernova.

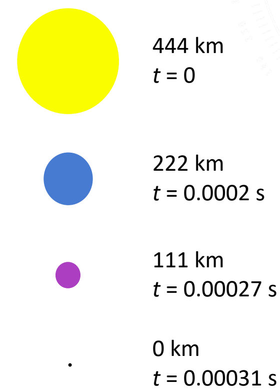
THE LAST FEW MOMENTS OF THE STAR

Space-time diagram of equatorial plane

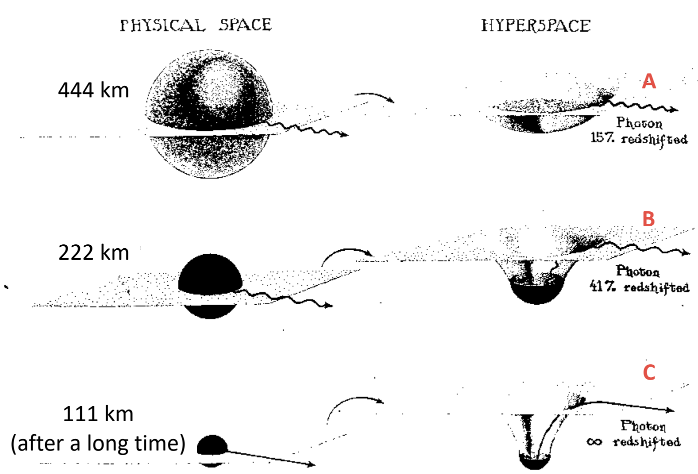


LAST FEW MOMENTS OF THE STAR TO AN OBSERVER ON THE SURFACE

Nothing happens as the star passes through its horizon circumference; the collapse keeps going until the mass is concentrated at a point, which takes very little time.



LAST FEW MOMENTS OF THE STAR TO A DISTANT OBSERVER



FOR MATH ADEPTS

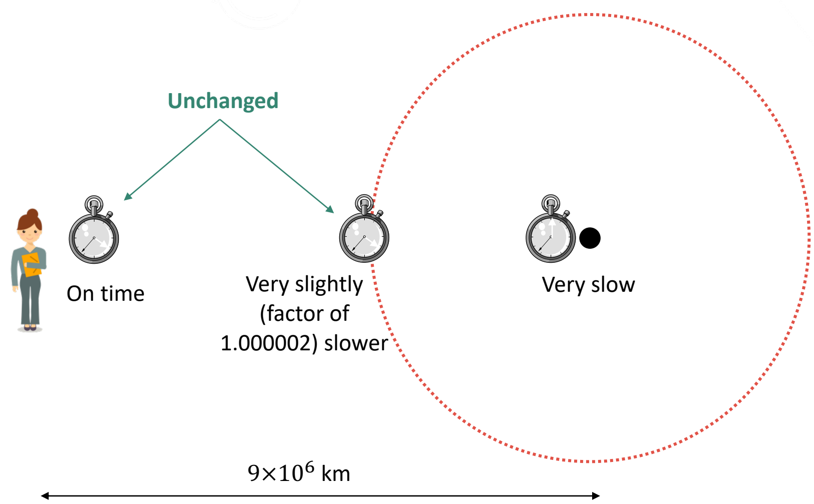
In case you are wondering where the numbers come from in the calculated results we are about to show, they come from equations that can be obtained fairly easily from the absolute interval that goes with the Schwarzschild metric, which we first saw a few lectures ago:

$$\Delta s^2 = \frac{\Delta r^2}{1 - \frac{4\pi GM}{Cc^2}} + \frac{C^2}{4\pi^2}\Delta\theta^2 + \frac{C^2}{4\pi^2}\sin^2\theta\,\Delta\phi^2 - c^2\left(1 - \frac{4\pi GM}{Cc^2}\right)\Delta t^2$$

We will not be showing (or making you use) these equations, but we can give you a personal tour of them if you like.

A $6M_\odot$ black hole is used throughout unless otherwise indicated.

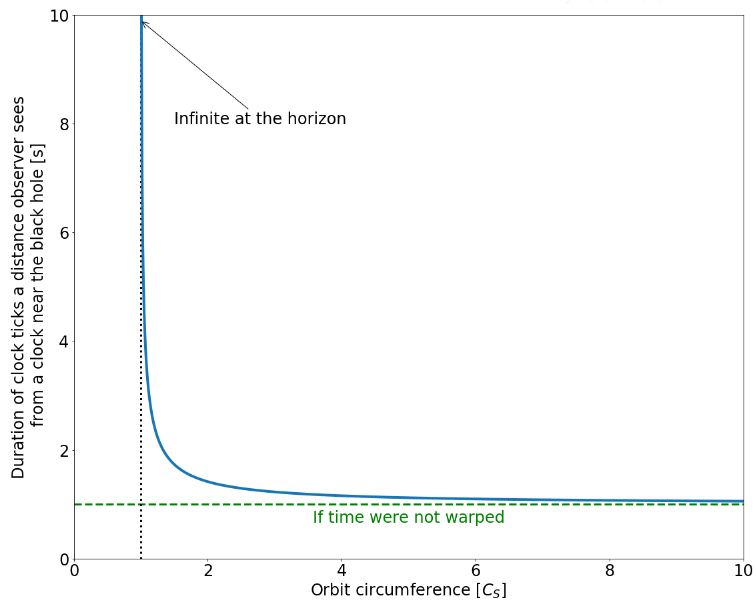
After:



SPACE AND TIME NEAR THE NEW BLACK HOLE

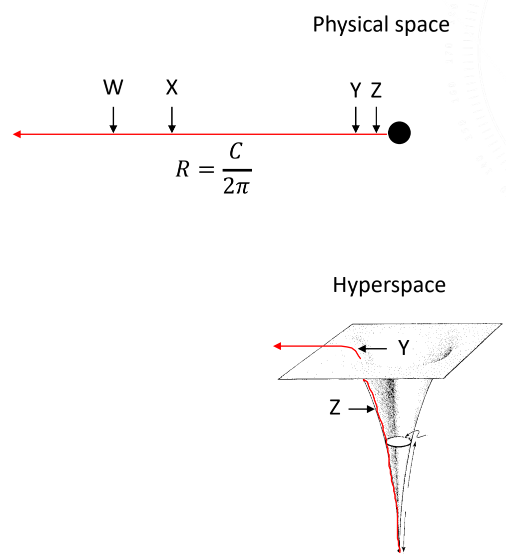
Time is warped in strong gravity.

GRAVITATIONAL TIME DILATION NEAR THE NEW BLACK HOLE

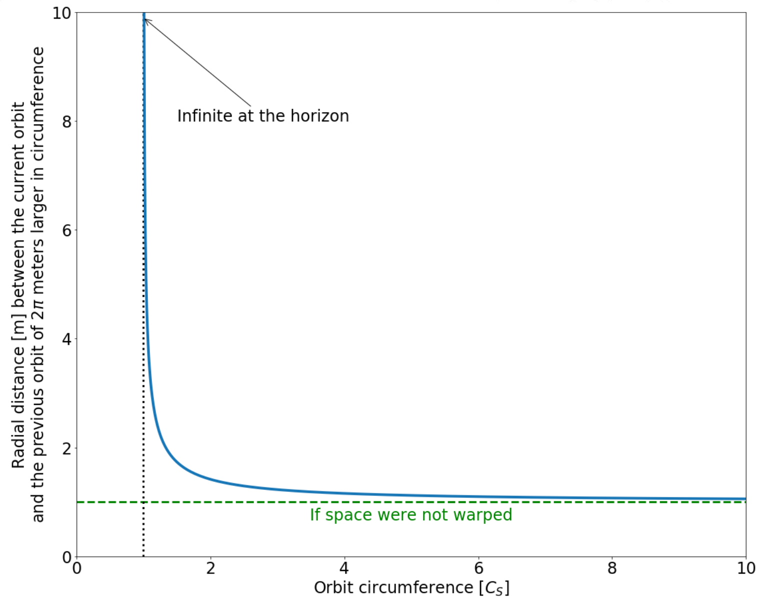


SPACE AND TIME NEAR THE NEW BLACK HOLE

Space is also strongly warped: for instance, for a local observer, points *Y* and *Z* are the same distance apart as points *W* and *X*.

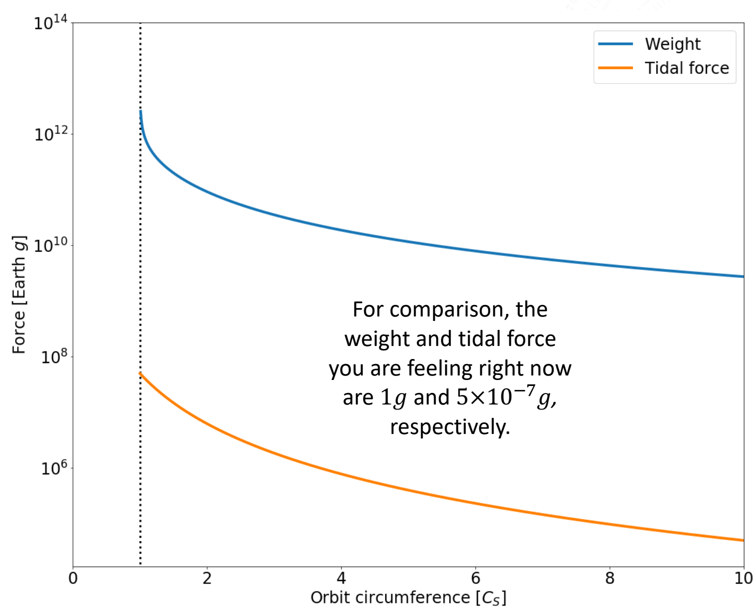


GRAVITATIONAL SPACE WARPING NEAR THE NEW BLACK HOLE



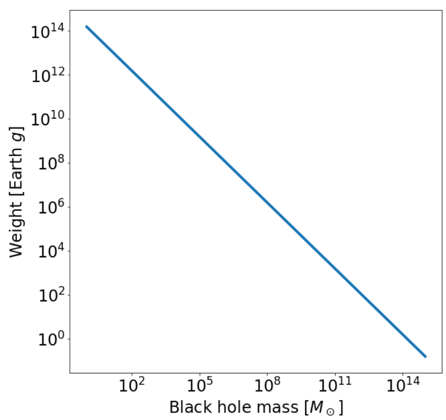
OTHER EFFECTS OF SPACE-TIME CURVATURE: WEIGHT & TIDES

The tides are for a 170 cm person lying along the radial direction toward the black hole.

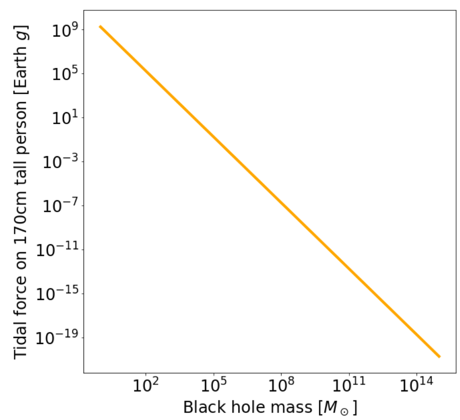


HOW WEIGHT & TIDES DEPEND UPON BLACK HOLE MASS

Weight

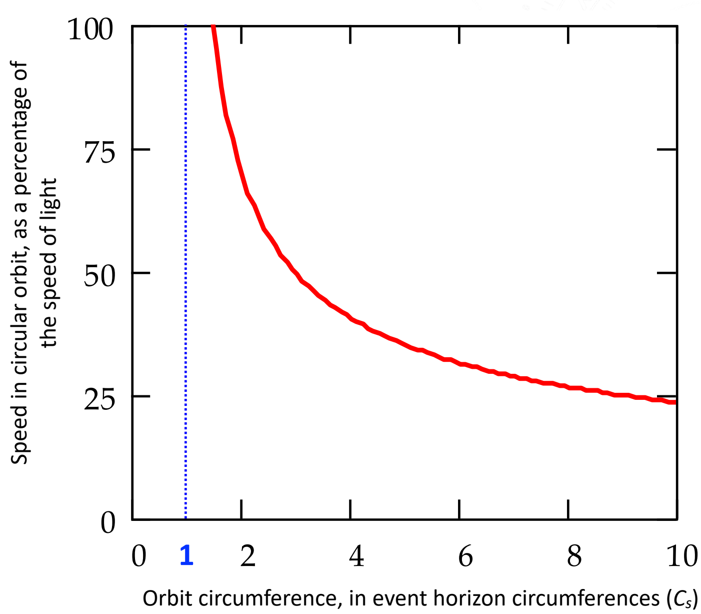


Tidal force



ORBITAL SPEED NEAR THE NEW BLACK HOLE

The orbital speed hits the speed of light at $1.5C_S$, so no closed orbits exist closer than this to the black hole.



TIME NEAR A DEAD STAR

You stand where the surface of a $6M_{\odot}$ star used to be, but which has collapsed into a black hole. From a great distance, I can see your clock, and it seems to tick

A. At the same rate as mine.
B. Very slightly slower than mine, as would also have been the case before the star collapsed and formed the black hole.
C. Very slightly slower than mine due to your proximity to the black hole.
D. Much slower than mine as would also have been the case before the star collapsed and formed the black hole.
E. Much slower than mine due to your proximity to the black hole.

TIME NEAR A DEAD STAR

You stand where the surface of a $6M_{\odot}$ star used to be, but which has collapsed into a black hole. You can see a nearby clock as well as your own, and that clock seems to tick

A. At the same rate as yours.
B. Very slightly slower than yours, as would also have been the case before the star collapsed and formed the black hole.
C. Very slightly slower than yours due to your proximity to the black hole.
D. Much slower than yours as would also have been the case before the star collapsed and formed the black hole.
E. Much slower than yours due to your proximity to the black hole.

“BLACK HOLES HAVE NO HAIR”

Meaning: After collapse is over with, the black hole horizon is smooth – nothing protrudes from it; almost everything about the star that gave rise to it has lost its identity during the black hole’s formation. No “hair” is left to “stick out.”

- Any protrusion, prominence, or other departure from spherical smoothness gets turned into **gravitational radiation**; it is radiated away during the collapse.
- Any magnetic field lines emanating from the star close up and get radiated away (in the form of light) during the collapse.
- The identity of the matter that made up the star is lost. Nothing about its previous configuration can be reconstructed.
- Even the distinction between matter and antimatter is lost: two stars of the same mass, but one made of matter and one made of antimatter, would produce identical black holes.

“BLACK HOLES HAVE NO HAIR”

The black hole has only three quantities in common with the star that collapsed to create it: **mass, spin, and electric charge**.

- Only very tiny black holes can have much electric charge; stars are electrically neutral, with equal numbers of positively- and negatively-charged elementary particles.
- Spin makes the black hole horizon depart from a spherical shape, but it is still smooth.

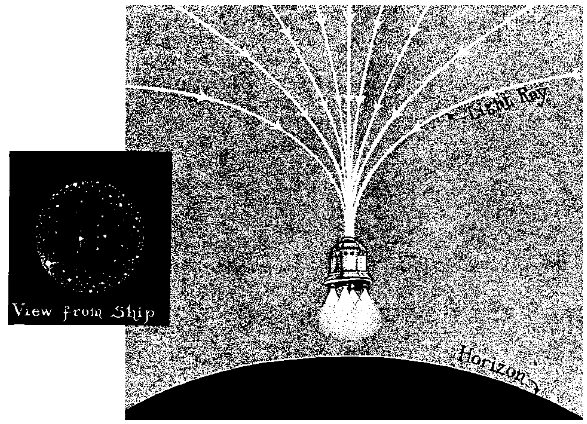
"SPACE AND TIME ARE STUCK AT BLACK HOLE HORIZONS"

Time is stuck at the event horizon.

- From the viewpoint of a distant observer, time appears to stop there (infinite gravitational time dilation).

Space is stuck at the event horizon.

- Inside a circle with $C = 1.5C_S$, all **geodesics** (paths of light or freely-falling masses) terminate at the horizon, because the orbital speed is equal to the speed of light at $C = 1.5C_S$: nothing can be in orbit closer than that.



"SPACE AND TIME ARE STUCK AT BLACK HOLE HORIZONS"

- Thus: From near the horizon, the sky appears to be compressed into a small range of angles directly overhead; the range of angles is smaller the closer you get to the horizon, and vanishes at the horizon. (The objects in the sky appear bluer than their natural colors as well, because of the gravitational Doppler shift.)
- Thus: Space itself is stuck to the horizon, since one end of each geodesic is there.

If the horizon were to move or rotate, the ends of the geodesics would move or rotate with it. Black holes can drag space and time around.

This is a **very** important effect, since virtually all black holes are expected to move and/or spin.

TIME DILATION

Gravitational time dilation approaches infinity – time is stuck – at a black hole's horizon. This means that, if you are just slightly outside the horizon of a black hole,

A. Everything appears to you to happen in slow motion.
B. Everything far away from the black hole appears to you to happen in slow motion.
C. Everything that you can see on the inside of the horizon appears to you to happen in slow motion.
D. You feel as if you are moving in slow motion.
E. To distant observers, you seem to be moving in slow motion.

COMPLEXITY

Which of these objects is the *simplest* to describe (requires the fewest details)?

A. A carbon atom
B. A single-cell organism
C. The Sun
D. A white dwarf
E. A black hole

SPINNING BLACK HOLES

Close enough to a rotating black hole, space-time is dragged around so well that it becomes impossible for a body to hover in such a way that they would appear stationary to a distant observer. This region is called the **ergosphere**.

The ergosphere represents a large fraction of the rotational energy of the black hole.

- 0-30% of the total energy of the black hole can be present in this rotation outside the horizon. (The faster it rotates, the higher the percentage.)
- There is a **maximum rotation rate** for which an object at the horizon would appear to be moving at the speed of light to a distant observer.

CROSS SECTIONS (THROUGH N & S POLES) OF SPINNING BLACK HOLES

Spin rate given as percentages of the maximum value.