ENERGY & BLACK HOLES

PROBLEM SET #5 AVAILABLE ON WEBWORK – DUE WEDNESDAY AT MIDNIGHT

HALLOWEEN EXTRA CREDIT!

ENERGY & BLACK HOLES

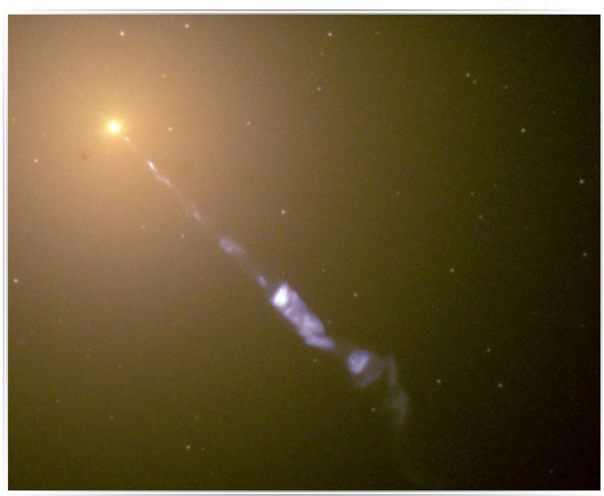
Spinning black holes

Black holes and gravitational radiation

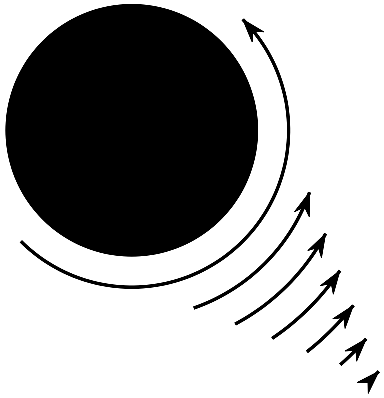
Einstein's mass-energy equivalence ($E = mc^2$)

Generation of energy from black holes

The search for black holes, part 1: the discovery of AGN and the evidence for the presence of black holes therein



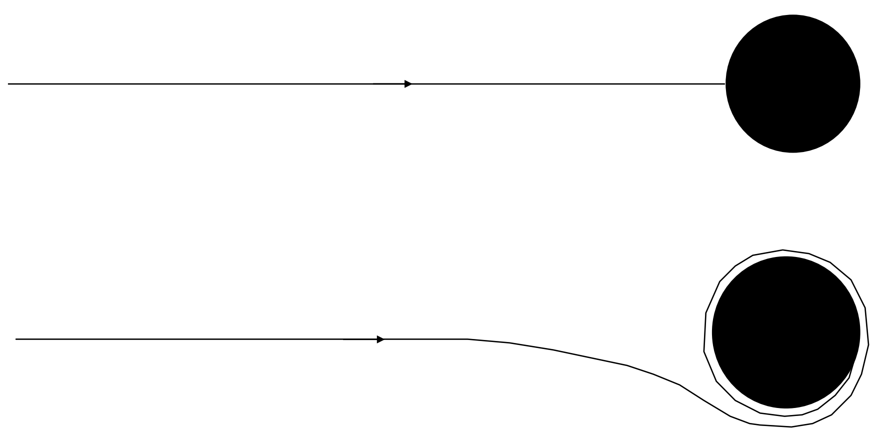
Jet and disk around a supermassive black hole in the center of the elliptical galaxy M87, as seen by the HST (NASA/STScI)



Motion of several bodies trying to hover motionless above the horizon of a spinning black hole, as seen by a distant observer above the north pole.

SPINNING BLACK HOLES

The closer to the horizon you are, the faster space seems to be rotating (Kerr 1964). This appears as a "tornado-like swirl" in hyperspace.



No spin

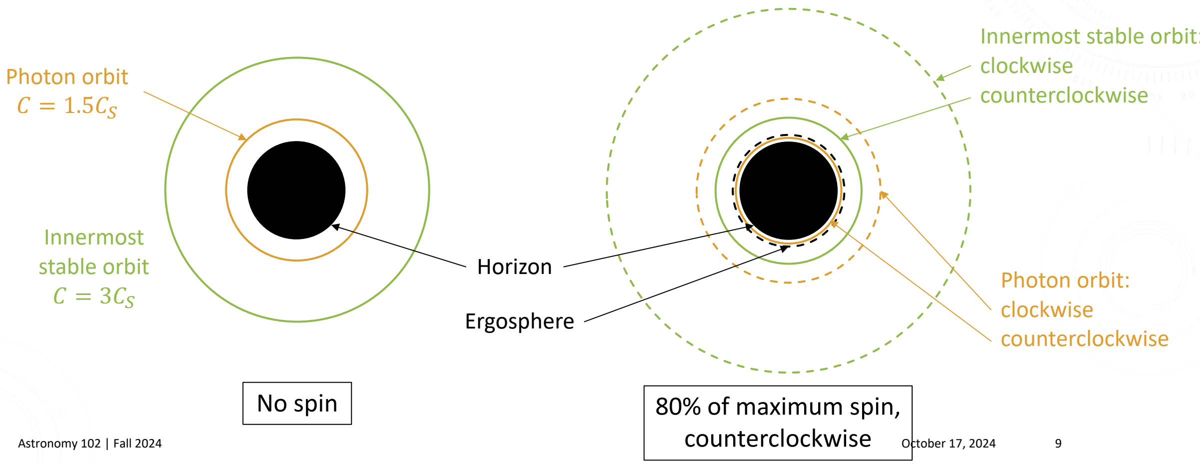
Spinning counterclockwise

SPINNING BLACK HOLES

"Straight" descent to the equator of a black hole, as it appears to a distant observer who looks down on the north pole.

STABLE ORBITS AROUND SPINNING BLACK HOLES

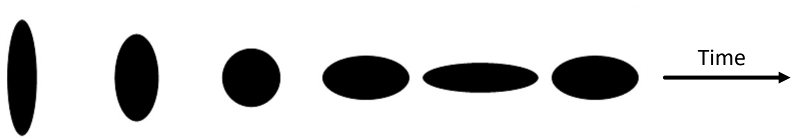
There exist stable orbits closer to spinning black holes than non-spinning ones. In the reference frame of a distant observer, anyway, and for orbits in the same direction as the spin. Here are two black holes with the same mass, viewed from a great distance above the north pole.



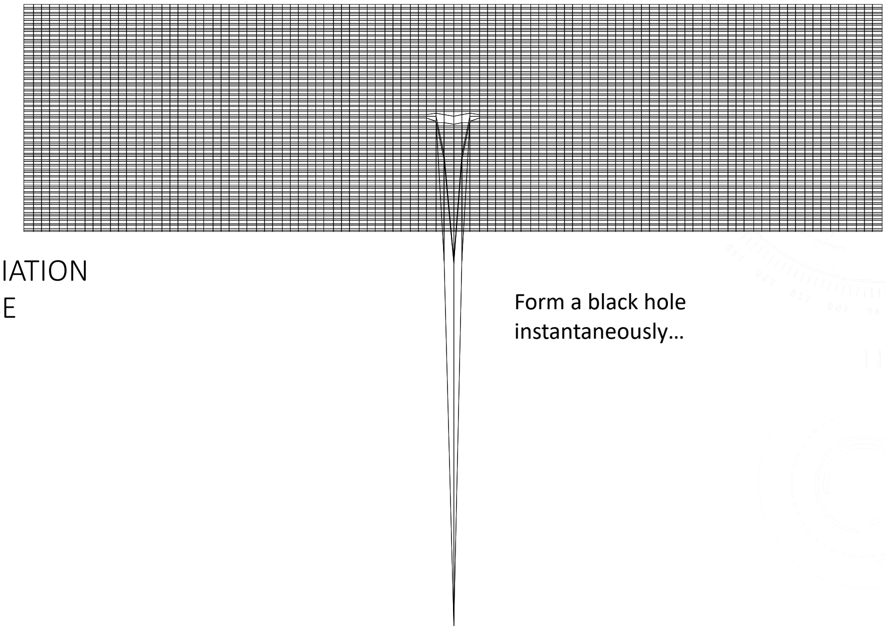
BLACK HOLES & GRAVITATIONAL RADIATION

Because space is stuck to event horizons, rapid changes in the size or shape of a black hole can generate gravitational radiation. The effect is often likened to ripples of curvature propagating through space-time, and in turn, to the ripples produced by throwing a rock in a pond. Examples:

- Formation of a horizon by stellar collapse
- Nonradial pulsation of a horizon: spindle through sphere to pancake and back again



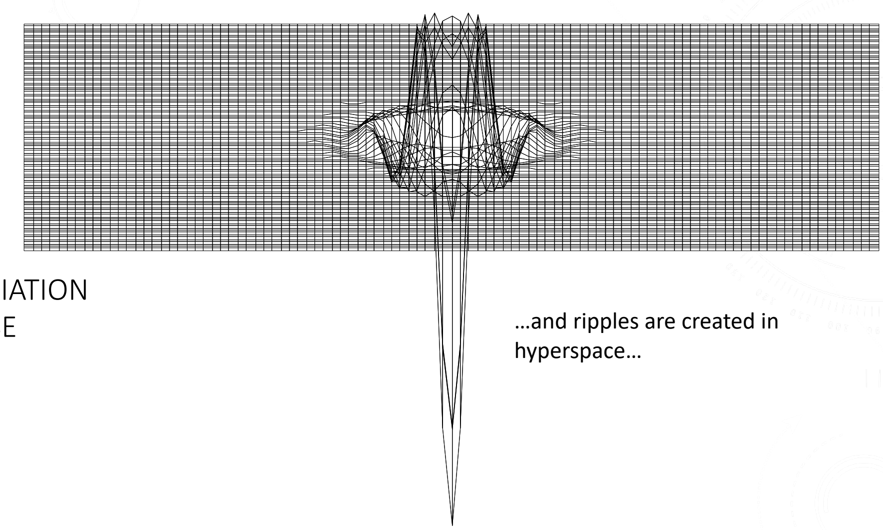
- Sudden growth of a horizon by the coalescence of two black holes



GENERATION OF GRAVITATIONAL RADIATION BY STELLAR COLLAPSE

View from hyperspace

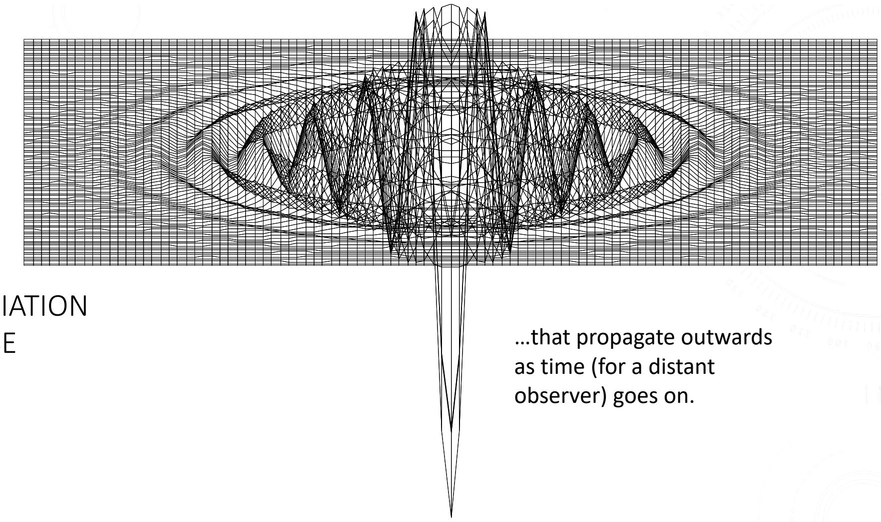
Form a black hole instantaneously…



GENERATION OF GRAVITATIONAL RADIATION BY STELLAR COLLAPSE

View from hyperspace

…and ripples are created in hyperspace…



GENERATION OF
GRAVITATIONAL RADIATION
BY STELLAR COLLAPSE

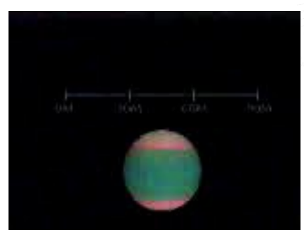
View from hyperspace

…that propagate outwards as time (for a distant observer) goes on.

BLACK HOLE PULSATION & GRAVITATIONAL RADIATION

Event horizons are easily "rung" when they are formed, or when the black hole accretes a substantial lump of mass.

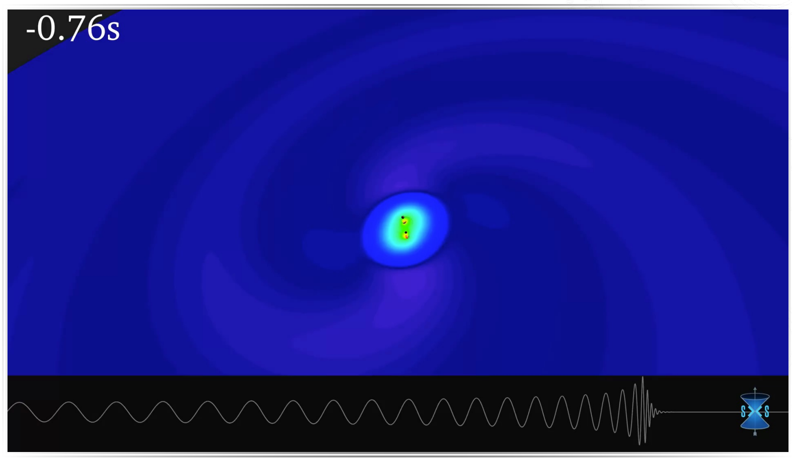
Simulations: the horizon of a small nonradial pulsation in a horizon (top), and the embedding diagram of the equatorial plane of a distorted black hole, showing emission of gravitational waves (bottom). By Ed Seidel et al. (NCSA/U. Illinois).



BLACK HOLE – BLACK HOLE COLLISION & GRAVITATIONAL RADIATION

The most energetic source of gravitational radiation yet conceived is the coalescence of two black holes.

Simulation: equatorial-plane embedding diagram for the inspiral and coalescence of two equal-mass black holes.



WHICH WOULD NOT GENERATE GRAVITATIONAL WAVES?

A. A stationary black hole spinning at a constant rate
B. Two black holes orbiting each other
C. Two neutron stars orbiting each other
D. The collapse of a star past the neutron-star limit

EQUIVALENCE OF MASS AND ENERGY IN EINSTEIN'S SPECIAL THEORY OF RELATIVITY

- **Mass is another form of energy.** Even at rest, in the absence of electric, magnetic, and gravitational fields, a body with (rest) mass m_0 has energy given by

$$E_0 = m_0 c^2$$

- Conversely, **energy is another form of mass.** For a body with total energy E, composed of the energies of its motion, its interactions with external forces, and its rest mass, the relativistic mass m is given by

$$m = \frac{E}{c^2}$$

You will need to know how to use these formulas!

EQUIVALENCE OF MASS AND ENERGY IN EINSTEIN'S SPECIAL THEORY OF RELATIVITY

Consequences:

- Even particles with zero rest mass (like photons) can be influenced by gravity, since their energy is equivalent to mass and mass responds to gravity (follows the curvature of space-time).
- There is an **enormous** amount of energy stored in rest mass.

NOTE ON ENERGY UNITS

- Since $E = mc^2$, the units of energy are

$$g\left(\frac{\text{cm}}{\text{s}}\right)^2 = \frac{\text{g cm}^2}{\text{s}^2} = \text{erg}$$

  - Luminosity is energy per unit time, so its units are erg/s, as we have seen.
- “Erg” comes from the Greek ‘érgon, which means “work” or “deed.”
- 1 watt = 1 W = 1 joule/s = 10^7 erg/s
- 1 joule $= 10^7$ erg
- 1 kWh = 1000 W × 1 hr $= 3.6{\times}10^{13}$ erg (power bill units)
- 1 megaton $= 4.18{\times}10^{22}$ erg (nuclear weaponry units)

EQUIVALENCE OF MASS & ENERGY IN EINSTEIN’S SPECIAL THEORY OF RELATIVITY

Example: Liberate energy, in the form of heat or light, from 1000 kg (1 metric ton) of anthracite coal.

- Burn it (turns it all into CO_2 and H_2O):

$$\Delta E = 4.3{\times}10^{17}\ \text{erg} = 12{,}000\ \text{kWh}$$

- Maximum efficiency fusion in a star (turns it all to iron):

$$\Delta E = 4.1{\times}10^{24}\ \text{erg} = 1.1{\times}10^{11}\ \text{kWh}$$

- Convert all of the coal’s rest mass (m_0) to energy (m_0c^2):

$$\Delta E = m_0c^2 = ?$$

$$\Delta E = m_0c^2 = (1{\times}10^6\ \text{g})(3{\times}10^{10}\ \text{cm/s})^2$$
$$\Delta E = 9{\times}10^{26}\ \text{ergs} = 2.5{\times}10^{13}\ \text{kWh}$$

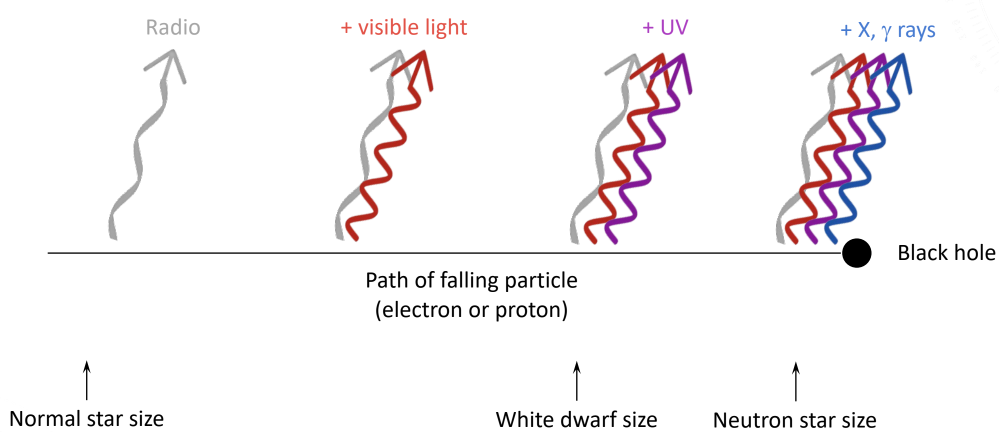
CONVERTING MASS TO ENERGY WITH A BLACK HOLE

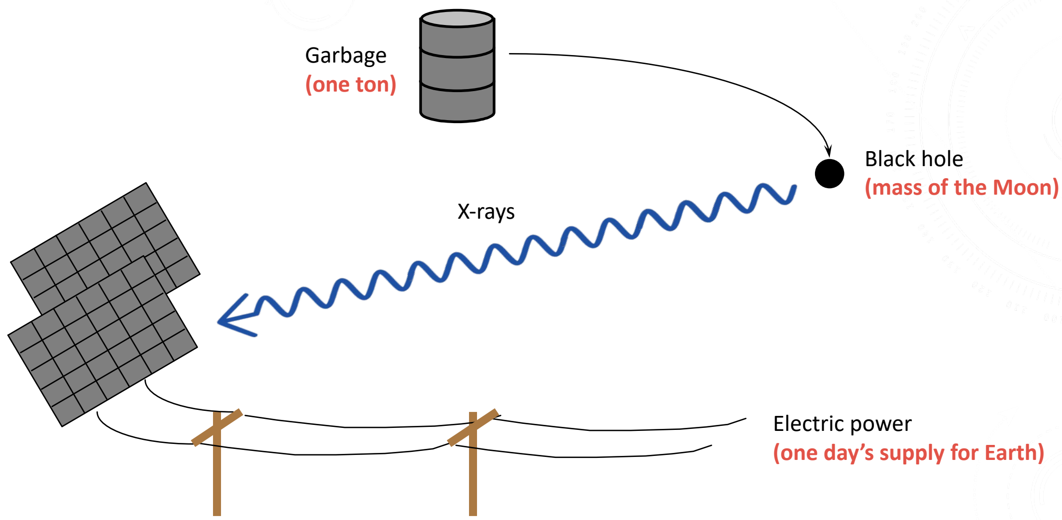
…by which we mean converting rest mass to heat or light.

Black hole accretion:

- As matter falls into a black hole, it is **ionized and accelerated** to speeds close to that of light and radiates light as it accelerates.
- The faster it goes, the higher the energy of the photons. The surface of planets or stars would stop an infalling particle before it approached the speed of light, but such speeds are possible when falling into a black hole.
- **About 10% of the rest mass of infalling particles can be turned into energy** (in the form of light) in this manner. **The other 90% is added to the mass of the black hole.**

CONVERTING MASS TO ENERGY WITH A BLACK HOLE





CONVERTING MASS TO ENERGY WITH A BLACK HOLE

Simultaneous solution of our energy and environmental problems?

CONVERTING MASS TO ENERGY WITH A BLACK HOLE

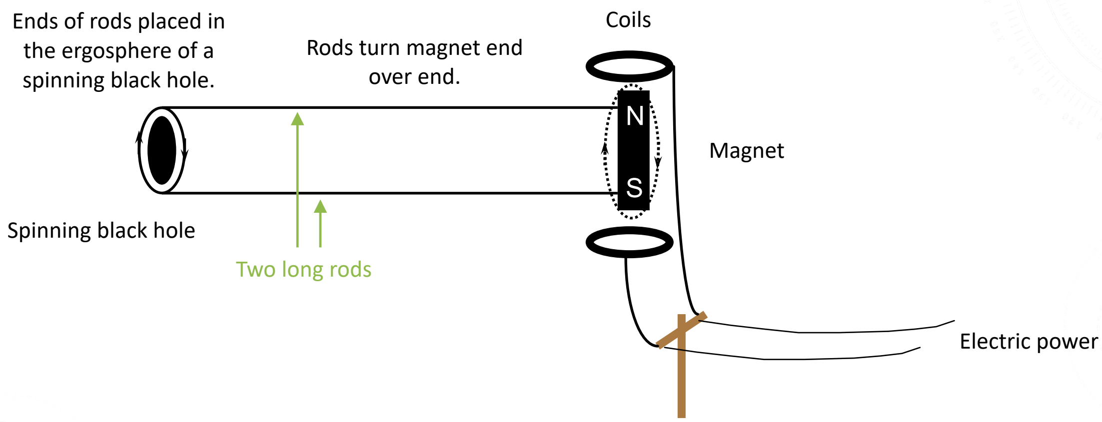
Spinning black holes (Penrose 1969, Blandford & Znajek 1977)

- Since space-time in the ergosphere rotates along with the horizon and 0-30% of the hole's total energy is there, a "crank handle" could be anchored to the ergosphere to have the black hole turn a distant motor.
  - This is a lot of energy: for a $10M_{\odot}$ black hole, 30% is

$$0.3m_0c^2 = 0.3(10)(2\times10^{33}\mathrm{g})(3\times10^{10}\ \mathrm{cm/s})^2 = 5.4\times10^{54}\ \mathrm{erg}$$

  - The Sun will emit "only" about 2×10^{51} erg in its entire life.
- The motor could be used to generate electricity at a fairly high efficiency until the hole stops spinning (a very long time).

SPINNING BLACK HOLE GENERATOR



GUESS ABOUT ACCRETION & ENERGY CONSERVATION

Energy is conserved – neither created nor destroyed, but often changed in form.

As a rock falls into a black hole, its speed (and *kinetic* energy) increases, so its mass (and relativistic mass-energy) increases. Something must therefore be losing energy – what?

A. It is drawing heat from the black hole's surroundings – material in the surroundings is cooling down.
B. Gravity is doing the work; the gravitational (binding) energy of the rock and the black hole must be decreasing.
C. The rock gets ionized and starts radiating light, UV, and X-rays, and this is an energy loss.
D. The rock would start burning up: chemical energy is lost.