Warm-up problem
Piglet:

“Wow, Tigger flew 15,000 meters!”
Piglet:
“Wow, Tigger flew 15,000 meters!”

What did I say?
Piglet:

“Wow, Tigger flew 15,000 meters!”

What did I say?

“I think you mean 1,500 meters. The last digit is tenths of a meter.”
Counter

150000

- How did I know this?
Hawking Radiation

• Black hole temperature
• Evaporation
• Micro black holes
• The LHC
Black Hole Surface Area

• Surface area of event horizon always increases in mergers or accretion

• Surface area is proportional to entropy of the black hole
BH Temperature

• For a black hole, $T = 6.135 \times 10^{-8} \left( \frac{M_\odot}{M} \right) \text{ K}$
  – Black body radiation

• Pointed out by Jacob Bekenstein in 1972

• How can a black hole radiate?
Virtual Particles near a BH

• If a pair of virtual particles is created near the event horizon,

• Hawking Radiation 1974
Hawking Radiation

- Black holes radiate energy!
- Mass of black hole decreases over time
- Entropy still does not decrease – heat carries away entropy
Hawking Radiation

• Wavelength of light emitted has a wavelength about equal to the size of the event horizon

• $\lambda \sim r_s = \frac{2GM}{c^2}$
Black Hole Evaporation

• For a black hole, \( T = 6.135 \times 10^{-8} \frac{M_{\odot}}{M} \) K

• Power per area =

\[ \sigma T^4 = 5.67 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ K}^{-4} T^4 \]
Black Hole Evaporation

• For a black hole, $T = 6.135 \times 10^{-8} \left( \frac{M_{\odot}}{M} \right) \text{ K}$

• Power per area = 
  
  $\sigma T^4 = 5.67 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ K}^{-4} T^4$

• Surface area = $16\pi G^2 M^2 / c^4$
Black Hole Evaporation

- For a black hole, $T = 6.135 \times 10^{-8} \left(\frac{M_\odot}{M}\right) \text{ K}$

- Power per area =
  $\sigma T^4 = 5.67 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ K}^{-4} T^4$

- Surface area = $16\pi G^2 M^2/c^4$

- Power = $9 \times 10^{-22} \left(\frac{M}{M_\odot}\right)^{-2} \text{ erg/s}$
Black Hole Evaporation

• Power = $9 \times 10^{-22} \ (M/M_\odot)^{-2} \text{ erg/s}$

• Power = $c^2 \times \text{ change in mass}$
Black Hole Evaporation

• Power = $9 \times 10^{-22} \left( \frac{M}{M_\odot} \right)^{-2} \text{ erg/s}$

• Power = $c^2 \times \text{ change in mass}$

• Change in mass = $-10^{-42} \left( \frac{M}{M_\odot} \right)^{-2} \text{ g/s}$
Black Hole Evaporation

- Power = $9 \times 10^{-22} \ (M/M_\odot)^{-2} \ \text{erg/s}$

- Power = $c^2 \times \text{change in mass}$

- Change in mass = $-10^{-42} \ (M/M_\odot)^{-2} \ \text{g/s}$

- Evaporation time = $6.67 \times 10^{74} \ (M/M_\odot)^3 \ \text{s}$
How long will it take for a 200 ton black hole to evaporate?

- Power = $9 \times 10^{-22} \left( \frac{M}{M_\odot} \right)^{-2}$ erg/s

- Evaporation time = $6.67 \times 10^{74} \left( \frac{M}{M_\odot} \right)^{3}$ s
How long will it take for a 200 ton black hole to evaporate?

• Power = $9 \times 10^{-22} \left(\frac{M}{M_\odot}\right)^{-2}$ erg/s

• Evaporation time = $6.67 \times 10^{74} \left(\frac{M}{M_\odot}\right)^3$ s

• Answer: 0.667 seconds
Black Hole Evaporation

• Any black hole that forms naturally will be more than a solar mass, so would take much longer than the age of the universe to evaporate

• Will also be colder than the CMB temperature, so will be growing, not shrinking.
Primordial Black Holes

• However, at the beginning of the Universe small black holes could form

• Gravitational collapse prevented by sound waves

• If a region is compact enough that it will collapse before the universe is old enough for a sound wave to cross, it becomes a BH
Density Fluctuations
What size black holes are evaporating now?

- Evaporation time $= 6.67 \times 10^{74} \ (M/M_\odot)^3 \ s$

- Age of universe $= 4.3 \times 10^{17} \ s$
What size black holes are evaporating now?

- Evaporation time = $6.67 \times 10^{74} \left(\frac{M}{M_\odot}\right)^3$ s

- Age of universe = $4.3 \times 10^{17}$ s

- $M = 1.7 \times 10^{14}$ g = 170 million tons
  - About a 23m wide asteroid

- Might be observable as GRBs?
What happens at the end of evaporation?

• Eventually, energy of photon emitted would be larger than mass-energy of black hole.
  – About a Planck mass

• No more radiation can be emitted?
• One last burst of particle and no remnant?
What is the smallest possible BH mass?

• Using general relativity, should be about a Planck mass, \(2 \times 10^{-5} \text{ g} = 2.4 \times 10^{18} \text{ GeV}\)

• But, depending on what theory of quantum mechanics and gravity we use, the mass could be much smaller

• Down to \(\sim 1000 \text{ GeV}\)
LHC

• Large Hadron Collider
LHC

- Will collide particles at very high energy, trying to make new particles
LHC

• Looking for Higgs Boson
• Predicted to exist in 1964, possibly found in 2012
LHC

- But, LHC could also make micro black holes
LHC

• What happens if you make a black hole?
LHC

- Probably the black hole will evaporate almost immediately
- Black holes evaporate over time
- Very slow for big ones, almost instantly for small ones
- This would be great!
LHC

• Possible, but unlikely, that black hole won’t evaporate, or at least not for a while
• But it will be very small and going almost the speed of light
• Will shoot through the Earth without hitting anything and keep going off into space
  – Collision like this happen all the time in the atmosphere and we’re still here