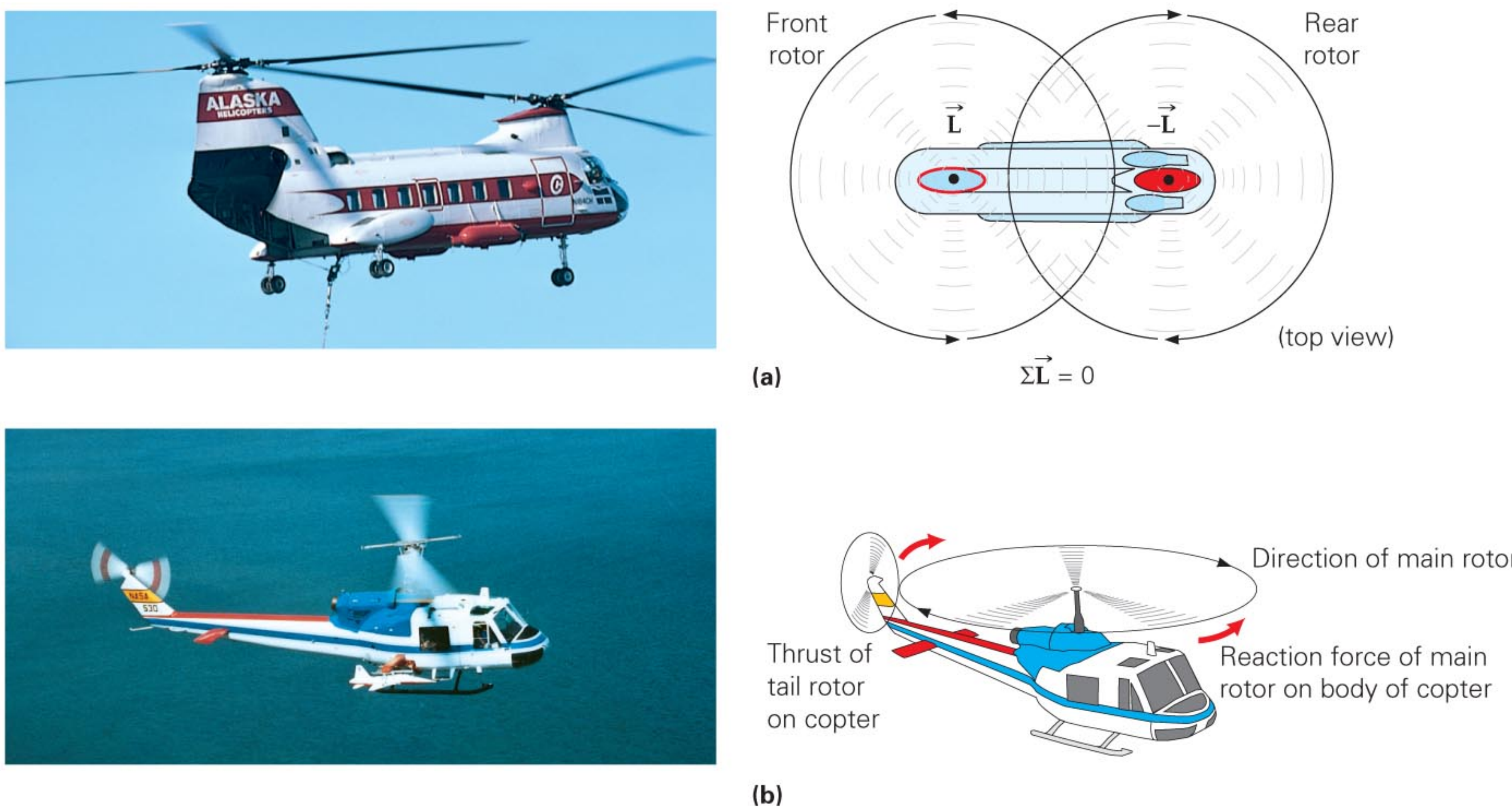
Physics 211

Sections 1 & 70
Dr. Geoffrey Lovelace
Fall 2012
Lecture 27 (12/13/12)

Angular momentum: helicopters

- Helicopter
  http://www.youtube.com/watch?v=nWk0jUfGrto



Lecture 27 outline

- Announcements
- Wave motion wrapup
  - Transverse vs. longitudinal
  - Interference
- Gravitational waves & black holes
- Final class participation (& followup if time permits)

Announcements

- Homework #11: due Thursday, 12/13 at 11:59PM
- Office hours
  - Today: 10AM-11AM, 4PM-5PM
  - Tuesday, December 18: 4PM-5PM
  - Wednesday, December 19: 3PM-5PM
    - McCarthy Hall room 601B
- Final exam December 20, 9:30AM-11:20AM
  - Skip the final? See me in office hours!
  - Emphasize material since Exam #3 (cumulative)

Today →

Date	Event
Nov 15	**Exam 3**
Nov 20	*Fall Recess — No class*
Nov 22	*Fall Recess — No class*
Nov 27	Rigid body rotation, torque
Nov 29	Rotational dynamics, rotational energy
Dec 4	Angular momentum, rigid body wrap-up *HW #10 due*
Dec 6	Harmonic motion
Dec 11	Harmonic motion & waves
Dec 13	Gravitational waves, harmonic motion, black holes, *HW #11 due*
Dec 20	**Final exam 9:30AM–11:20AM**

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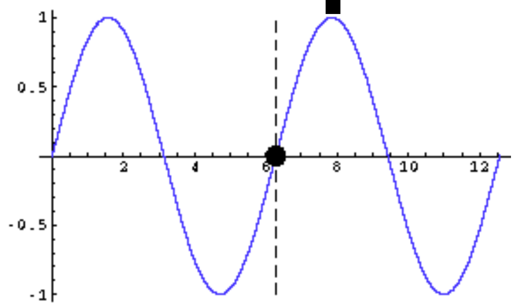
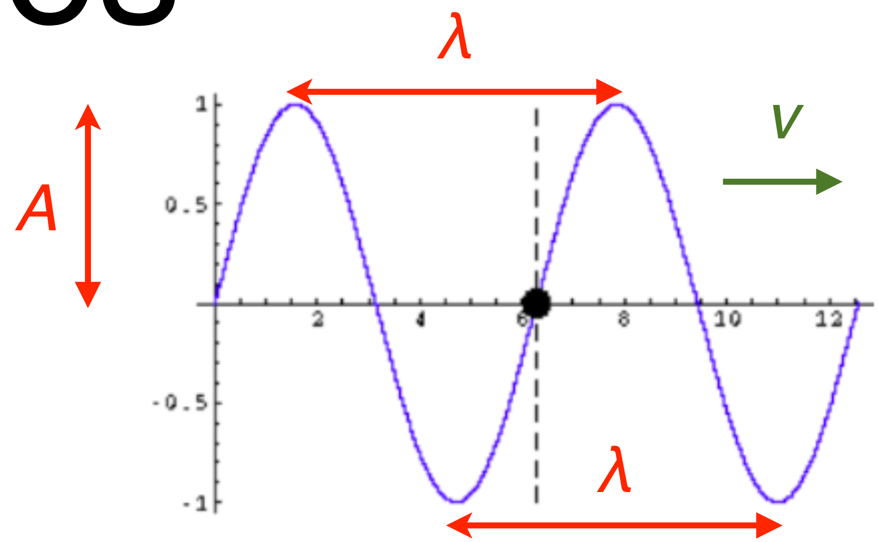
Wave properties



$$y = A\sin\left[2\pi\left(\frac{x}{\lambda}-\frac{t}{T}\right)\right]$$



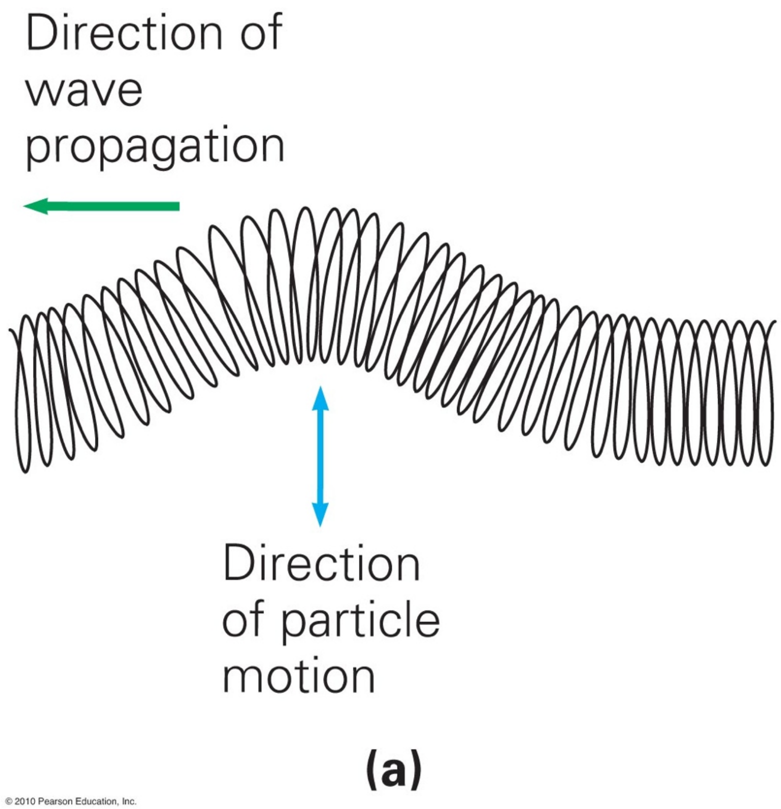
$$v = \lambda/T = \lambda f$$

$$T = \frac{1}{f}$$

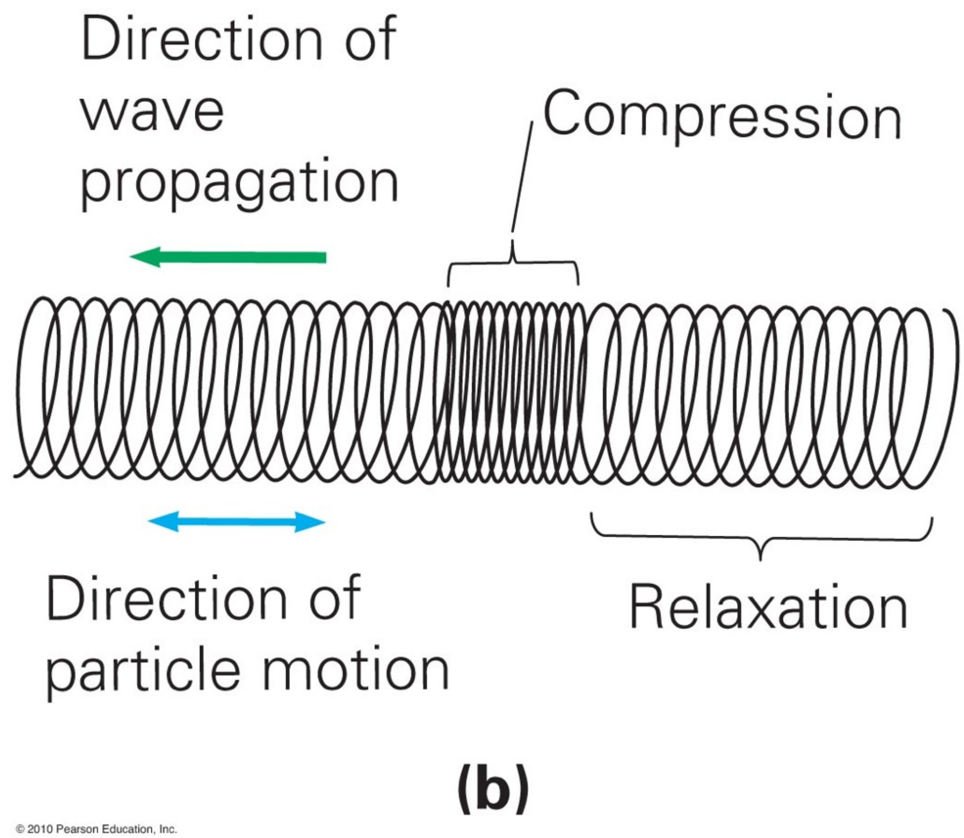
- Amplitude A = max. displacement
- Wavelength λ = crest-to-crest distance
- Period T = time for one wavelength to go by a given point
- Frequency f = number of wavelengths per second to go by
- Wave speed v = speed wave travels = 1 wavelength / period

Longitudinal & transverse

Transverse



Longitudinal



Clicker question #123

Question 13.14 The Wave

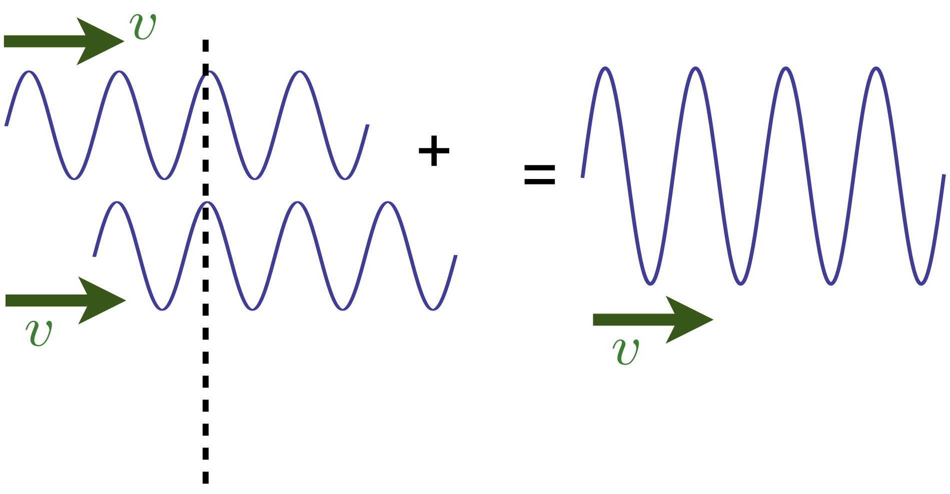
At a football game, the "wave" might circulate through the stands and move around the stadium. In this wave motion, people stand up and sit down as the wave passes. What type of wave would this be characterized as?

A. longitudinal wave
B. transverse wave
C. both longitudinal & transverse
D. neither longitudinal nor transverse

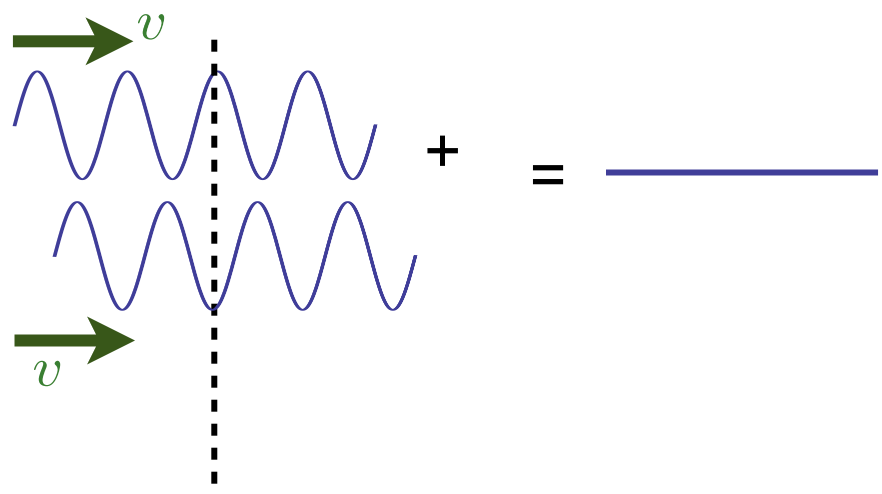
Interference

- Superposition principle: combined wave = wave 1 + wave 2

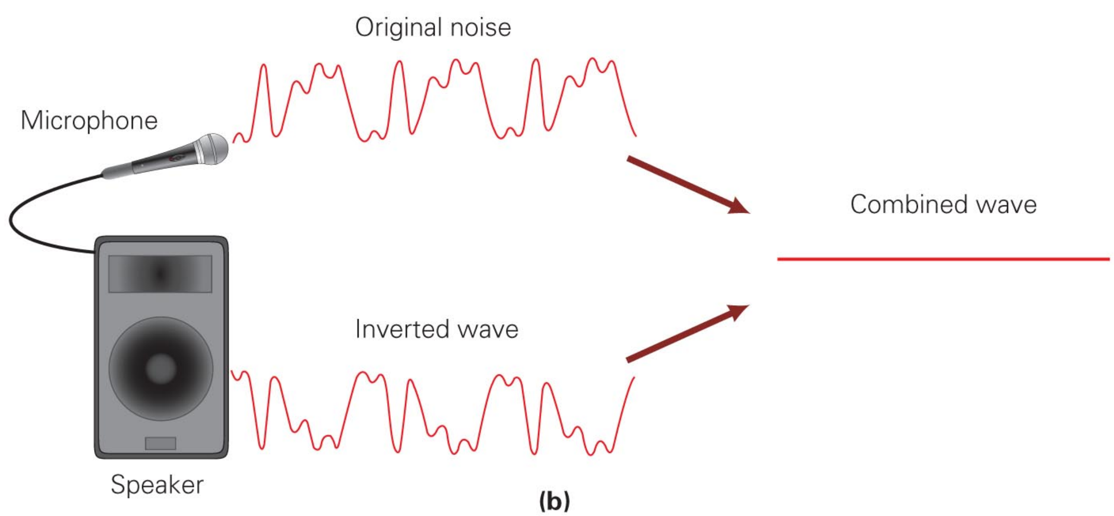
Constructive



Destructive

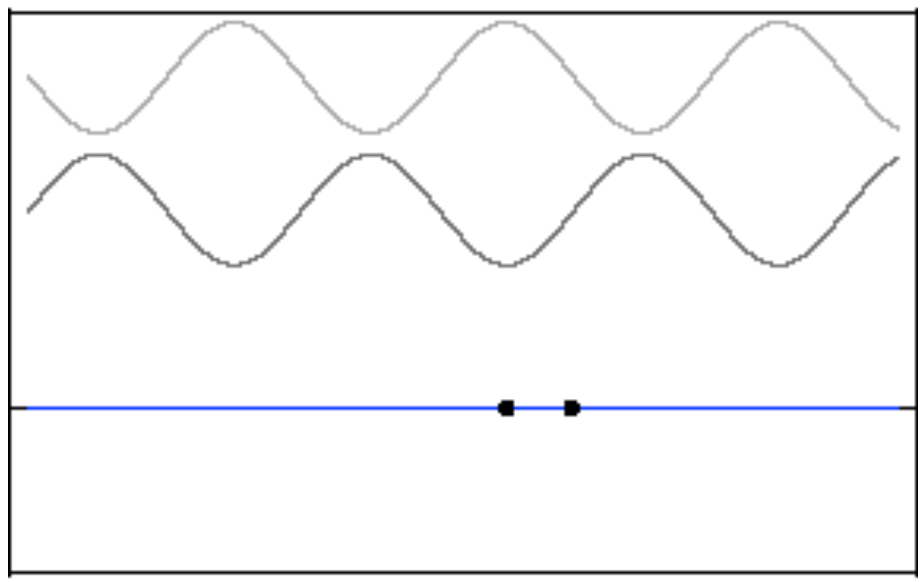


- Application: noise-canceling headphones, mufflers



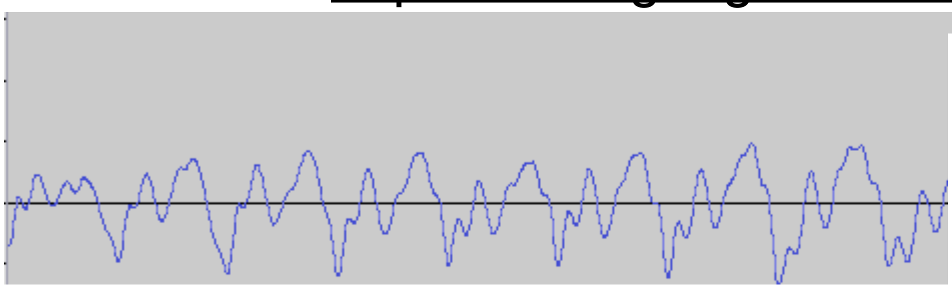
Standing wave

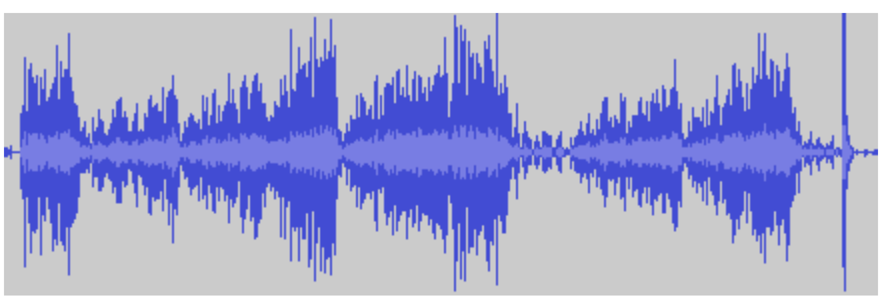
- Wave moving left + wave moving right

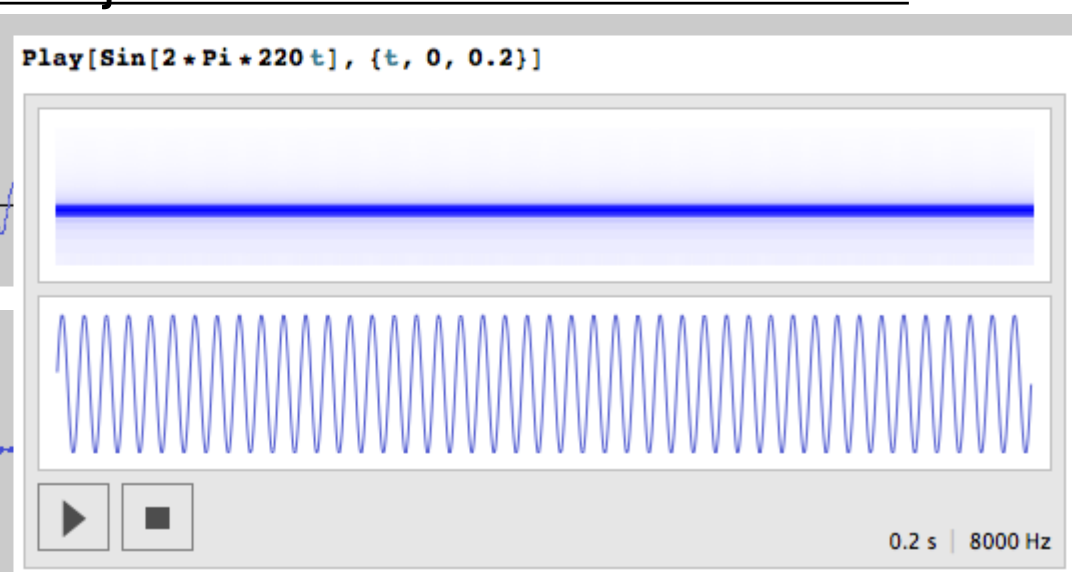


Examples of waves

- Transverse, wave speed = speed of light
- Longitudinal, wave speed = speed of sound = 340 m/s
  - Sound waves
    - Frequency f = 440 Hz for “A” above middle “C”
    - Double (halve) frequency to go up (down) octave
    - Music: superposition of many different sinusoidal waves https://sites.google.com/site/jasonrlovelace/scores-and-audio







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Images courtesy wikipedia

What are black holes?

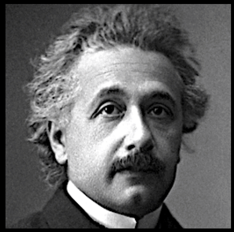
- Gravity

Newton (1687)

Masses attract

Force $\sim$ (Mass 1)(Mass 2) / (Separation)^2

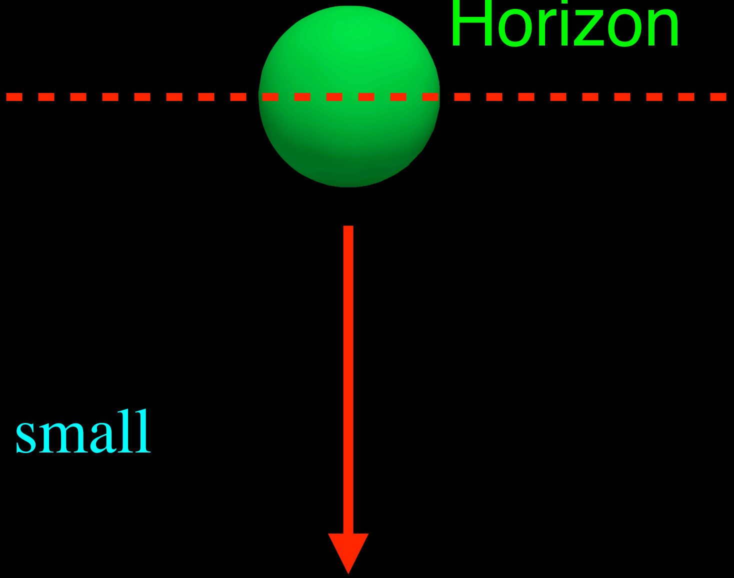
OK if gravity is weak, velocities small

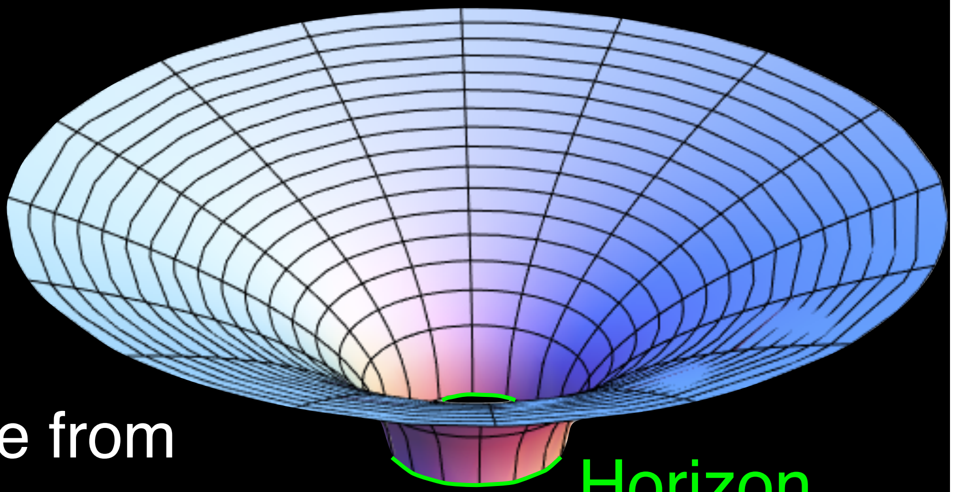


Einstein (1915)

General Relativity: gravity result of warped spacetime

Mass causes warping





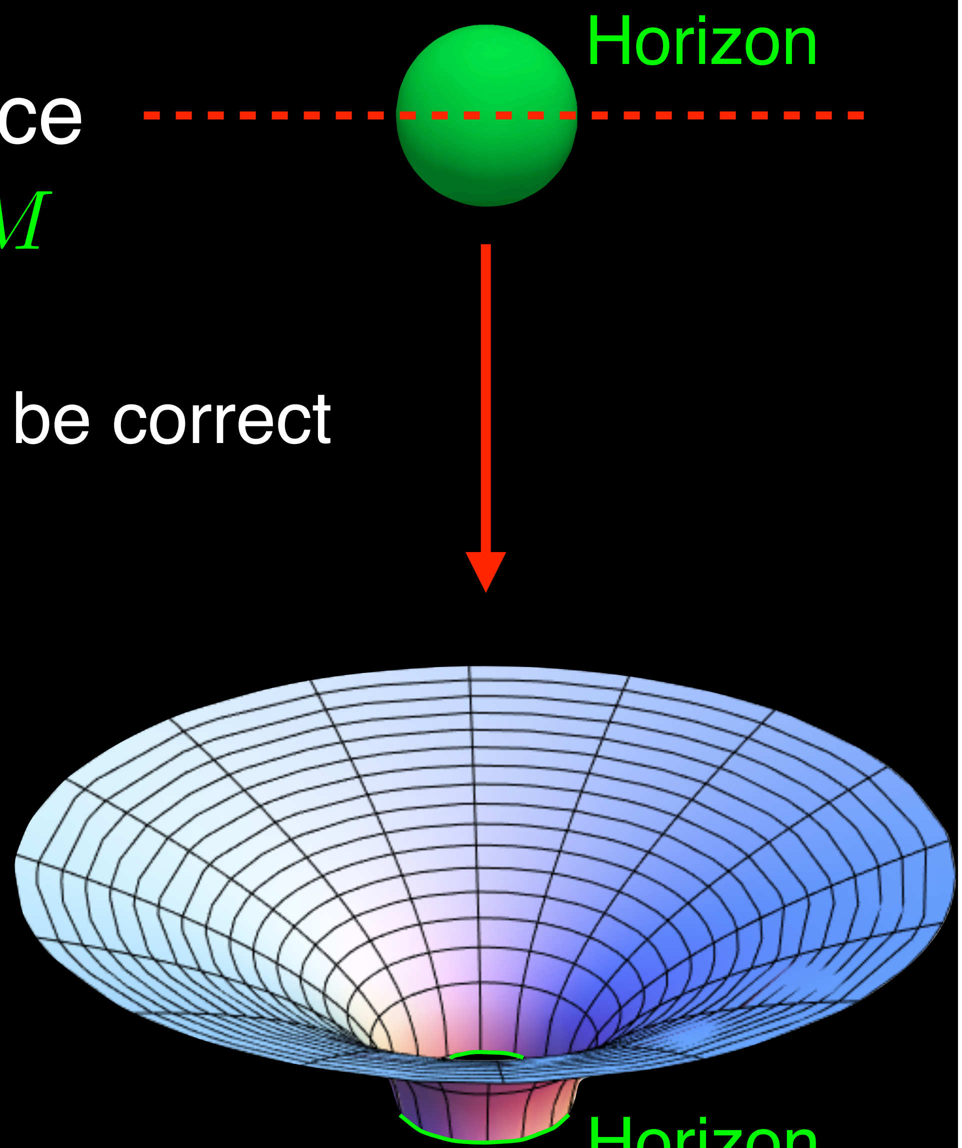
- Black holes
  - –Gravity so strong...
    - Nothing (even light) can escape from inside hole's horizon (surface)
    - Singularity inside horizon: infinitely strong gravity

How big are black holes?

- Horizon: black hole's surface
  - –Size R_H set by hole's mass M
  - –Can derive with GR, but Newtonian result turns out to be correct
    - Energy conservation & Newtonian gravity & "escape velocity = speed of light"

$$-\frac{GMm}{R_H} + \frac{1}{2}mc^2 = 0$$

$$\Rightarrow R_H = \frac{2GM}{c^2}$$



$c = \text{Speed of light}$

$G = \text{Gravitational constant}$

How big are black holes?

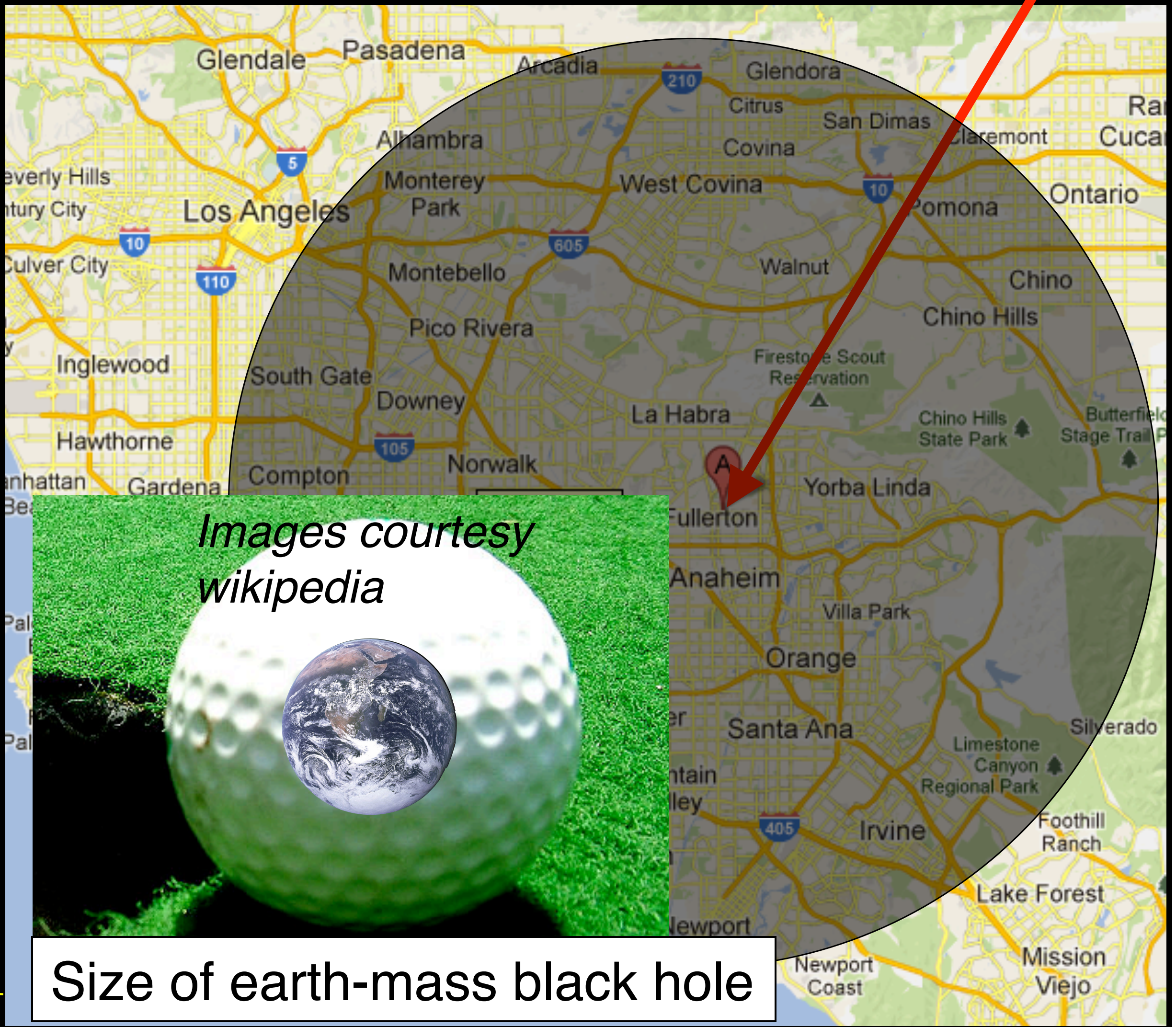
- Massive
  - Stellar: ≈ 3 - 30 solar masses
  - Supermassive: Millions - billions solar masses
- Compact

$$R_H = \frac{2GM}{c^2}$$

$$= \left(\frac{\text{Mass}}{\text{Solar mass}}\right) \times 3 \text{ km}$$

$$= \left(\frac{\text{Mass}}{\text{Earth mass}}\right) \times 9 \text{ mm}$$

You are here



Size of 10-solar-mass black hole

Image courtesy Google maps

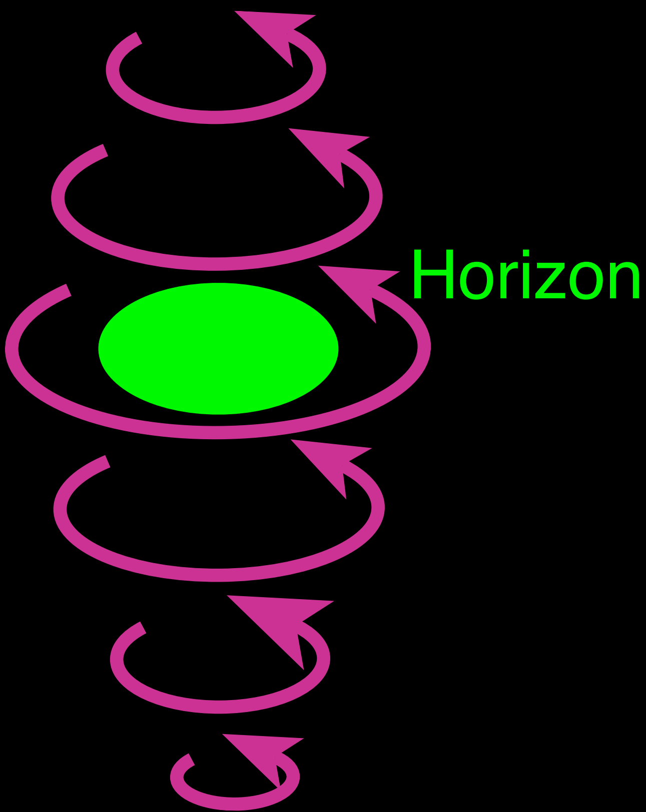
Clicker question #125

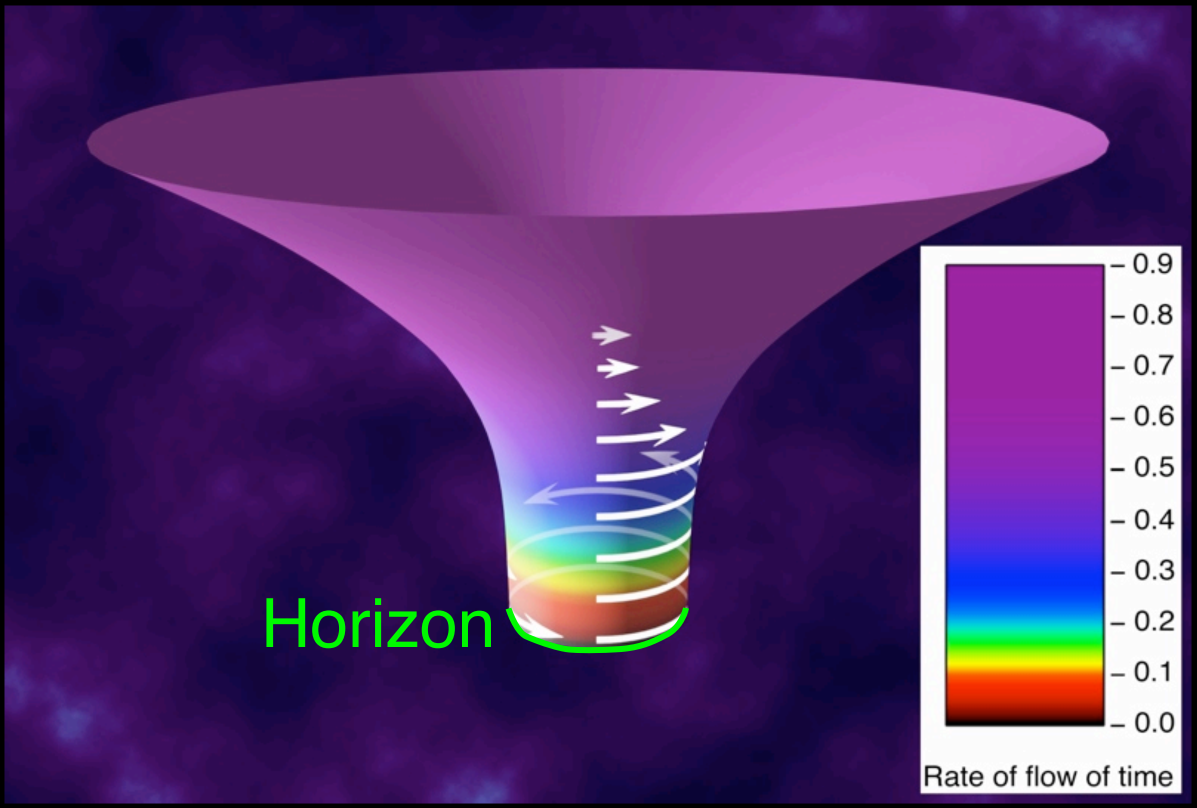
- Enough matter falls into a black hole that its circumference doubles. The hole's mass is now _______________.

  - A 2 times smaller.
  - B Unchanged.
  - C 2 times larger.
  - D Not enough information given to know.

Black holes rotate (have angular momentum)

- Whirl space like a tornado





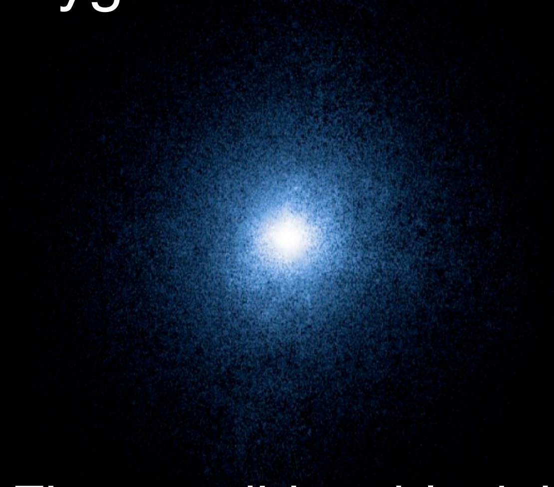
Images courtesy Kip Thorne

Images courtesy NASA

Observing black holes

- Black holes are black…how to observe?
  - –Indirectly
    - Gravity affects motion of objects nearby: infer mass
    - Gas heats up & glows as it falls in: infer spin (uncertain!)

Cygnus X-1

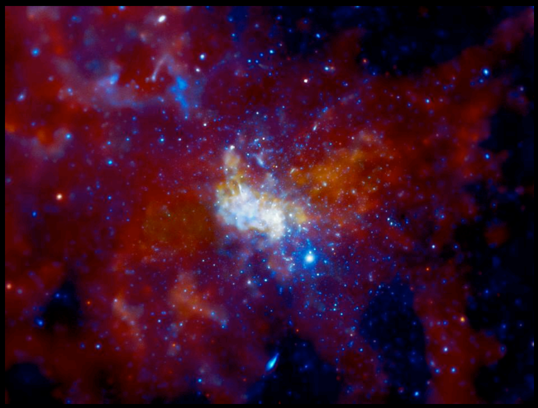


First candidate black hole discovered

$M/M_{\mathrm{sun}} \approx 15$

$\chi \gtrsim 0.95$ — Gou *et al.* (2011)

Sagittarius A*



Black hole at center of our galaxy

$M/M_{\mathrm{sun}} \approx 4 \times 10^6$

$\chi \approx 0$ —Broderick *et al.* (2010)

–Directly: *waves of gravity* from colliding black holes

What are gravitational waves?

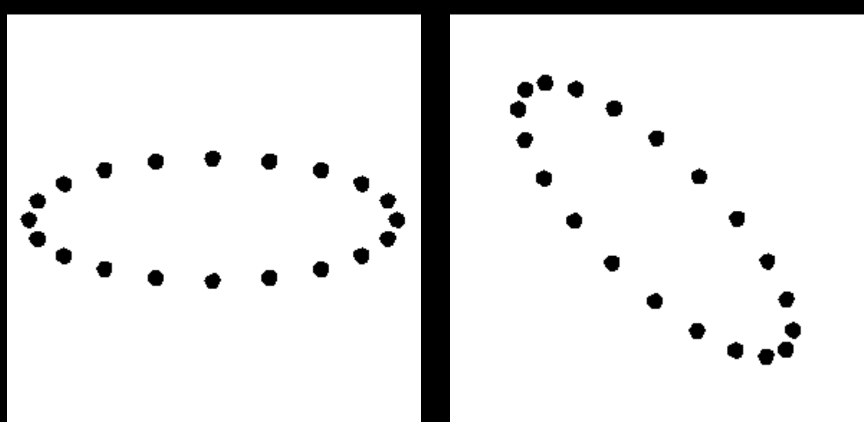
Gravitational waves

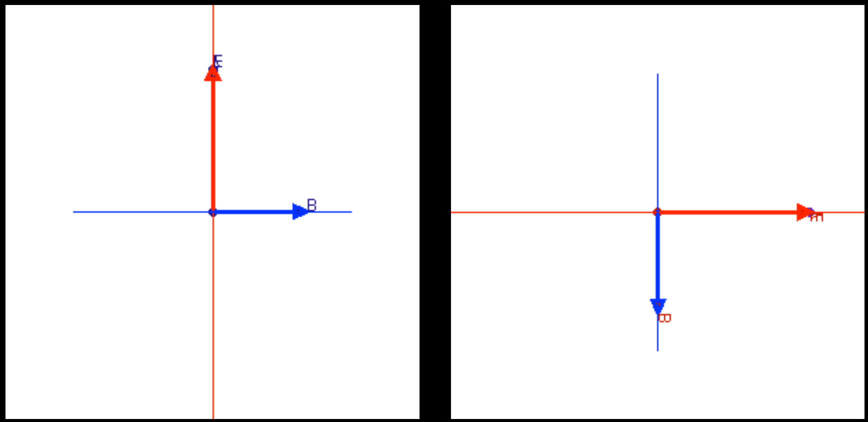
- Propagate at speed of light
- Transverse
- 2 polarizations
- 180-degree symmetric
- Tidal deformation oscillates

Electromagnetic waves

- Propagate at speed of light
- Transverse
- 2 polarizations
- 360-degree symmetric
- Electric & magnetic fields oscillate

plane wave into screen

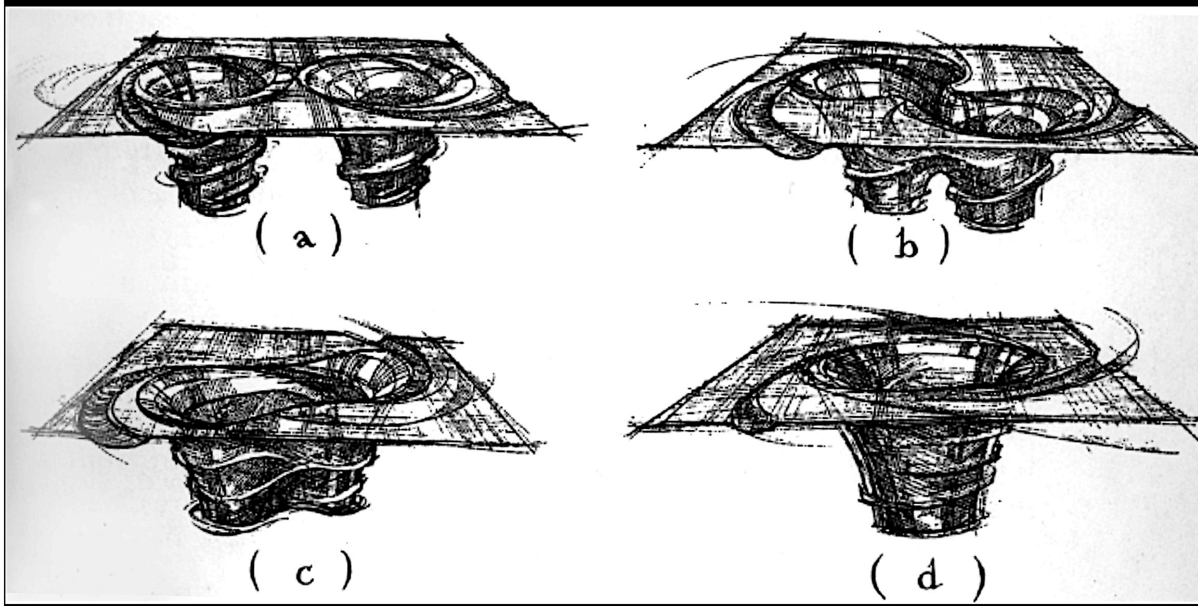


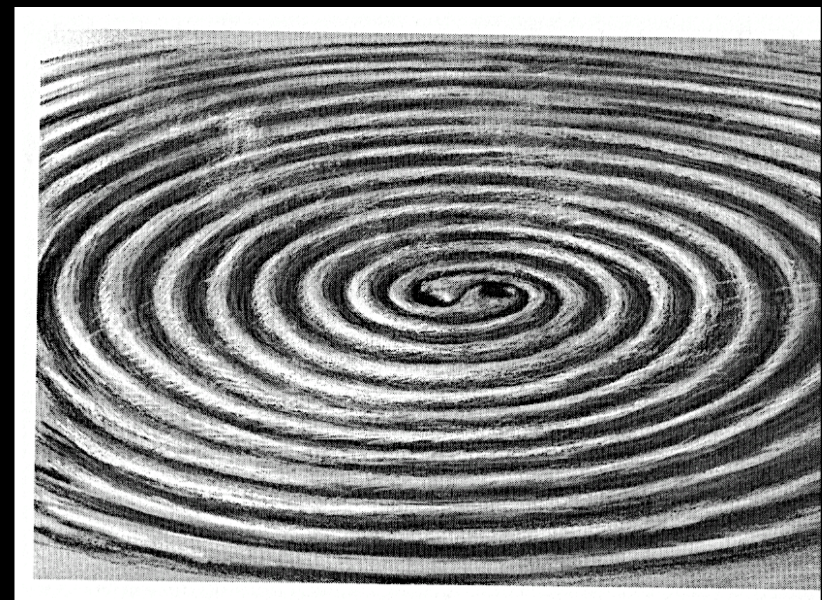


Images courtesy wikipedia

Colliding black holes

- Inspiral, merger, ringdown: emit gravitational waves





- –Most violent events in the universe
  - Radiate ~10% of holes' mass (vs. ~0.5% nuclear fusion)
- –Invisible! No light emitted at all.
  - Except, e.g., if gas in disk around hole disturbed

Images courtesy Kip Thorne, LIGO

Detecting gravitational waves

- Ripples of warped spacetime
  - Weak when arrive at earth (black holes far away)
  - As wave goes by & space warps detector arm lengths (4 km) stretch & squeeze slightly (10^{-18} m)

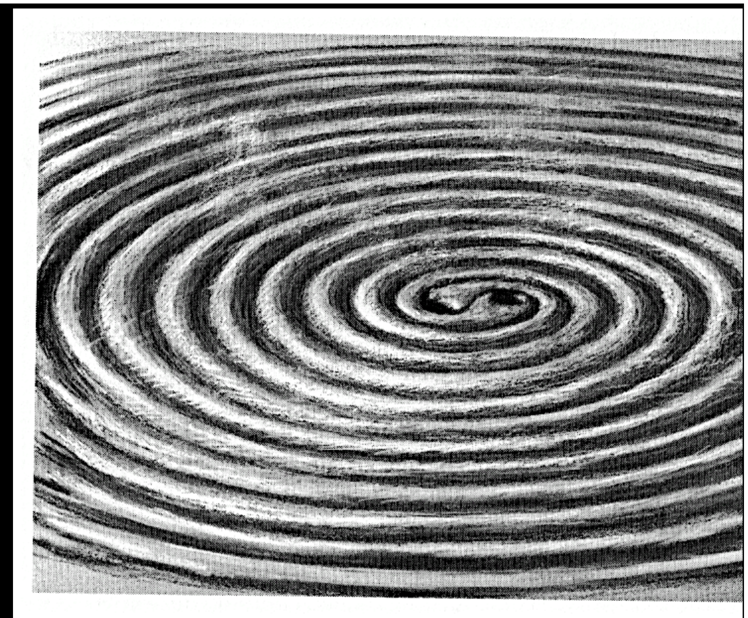


Image courtesy Kip Thorne, LIGO

1 m	Human height
÷ 10000	Human hair width
÷ 100	Wavelength of light
÷ 10000	Size of atom
÷ 100000	Size of nucleus
÷ 1000	10^{-18} m (LIGO)

- Measure using lasers

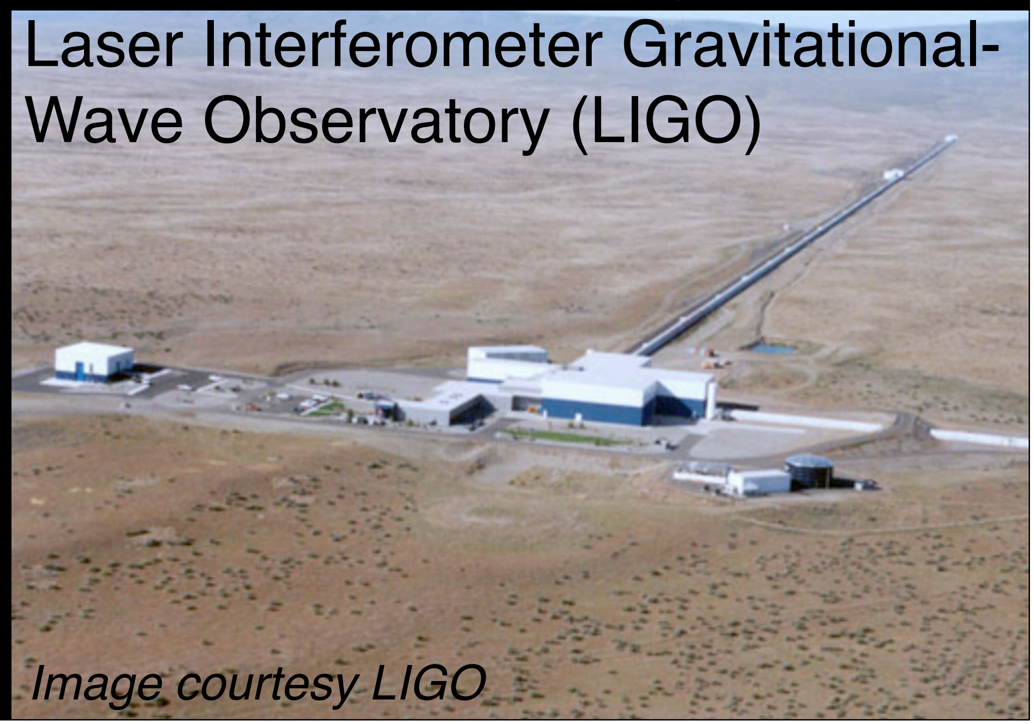


Image courtesy LIGO

Simulation of merging black holes

Dictionary:

- Holes' horizons & trajectories
- Warped spacetime

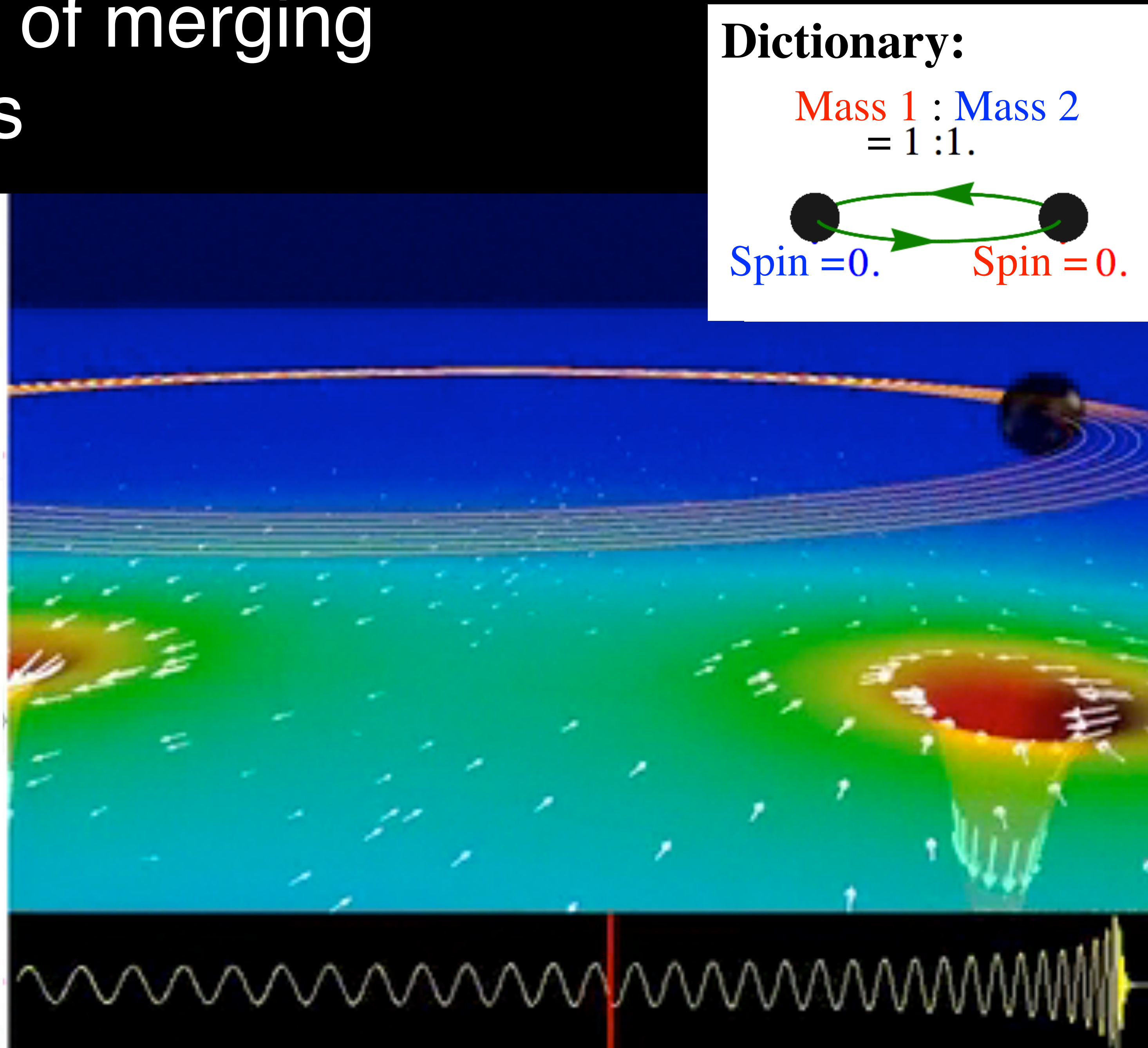
- *Depth: space warping*

- *Colors: flow of time*

- *Arrows: flow of space*

Catalog:

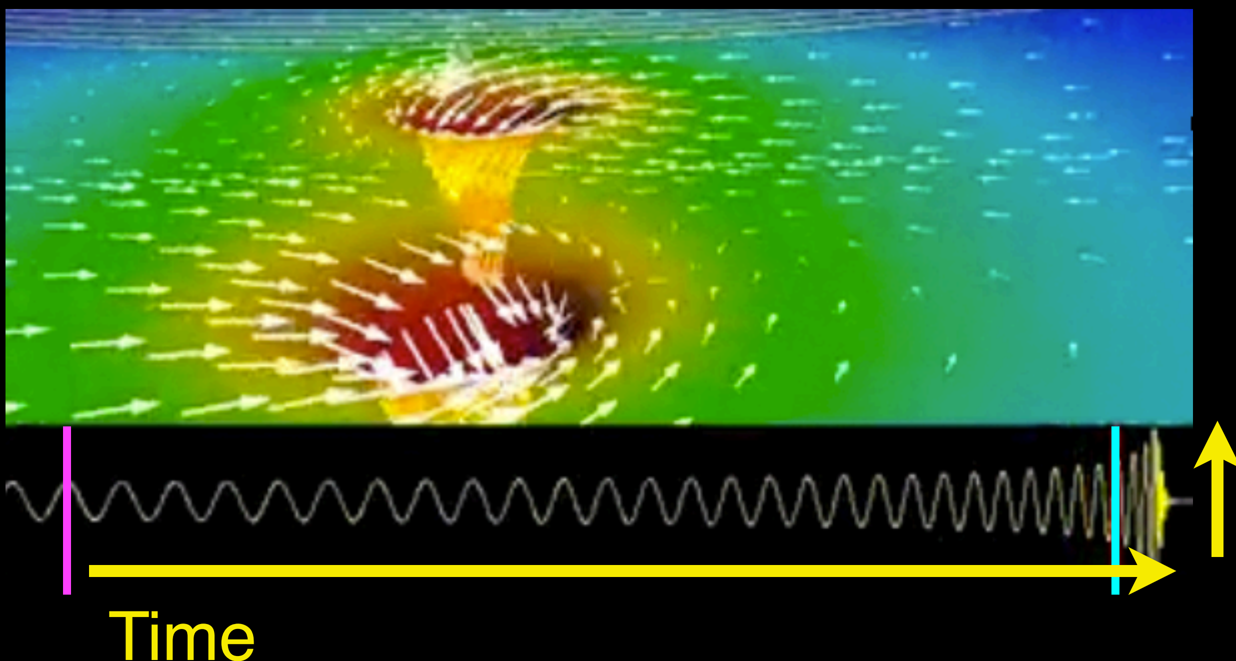
- Waveform



Movie courtesy Harald Pfeiffer

Clicker question #127

- The graph below shows what a detector would observe as a gravitational wave from two merging black holes went by. Compared to the earlier time, at the current time shown, the gravitational-wave **amplitude** is



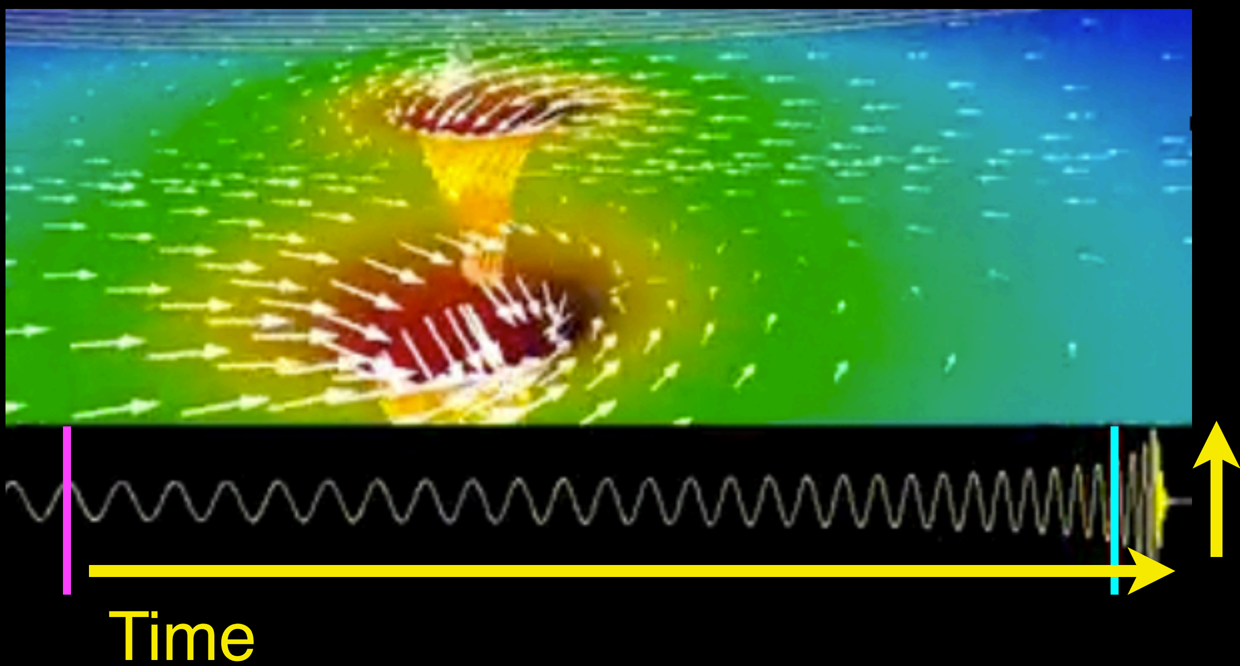
A Smaller

B Larger

C Unchanged

Clicker question #128

- The graph below shows what a detector would observe as a gravitational wave from two merging black holes went by. Compared to the earlier time, at the current time shown, the gravitational-wave **frequency** is



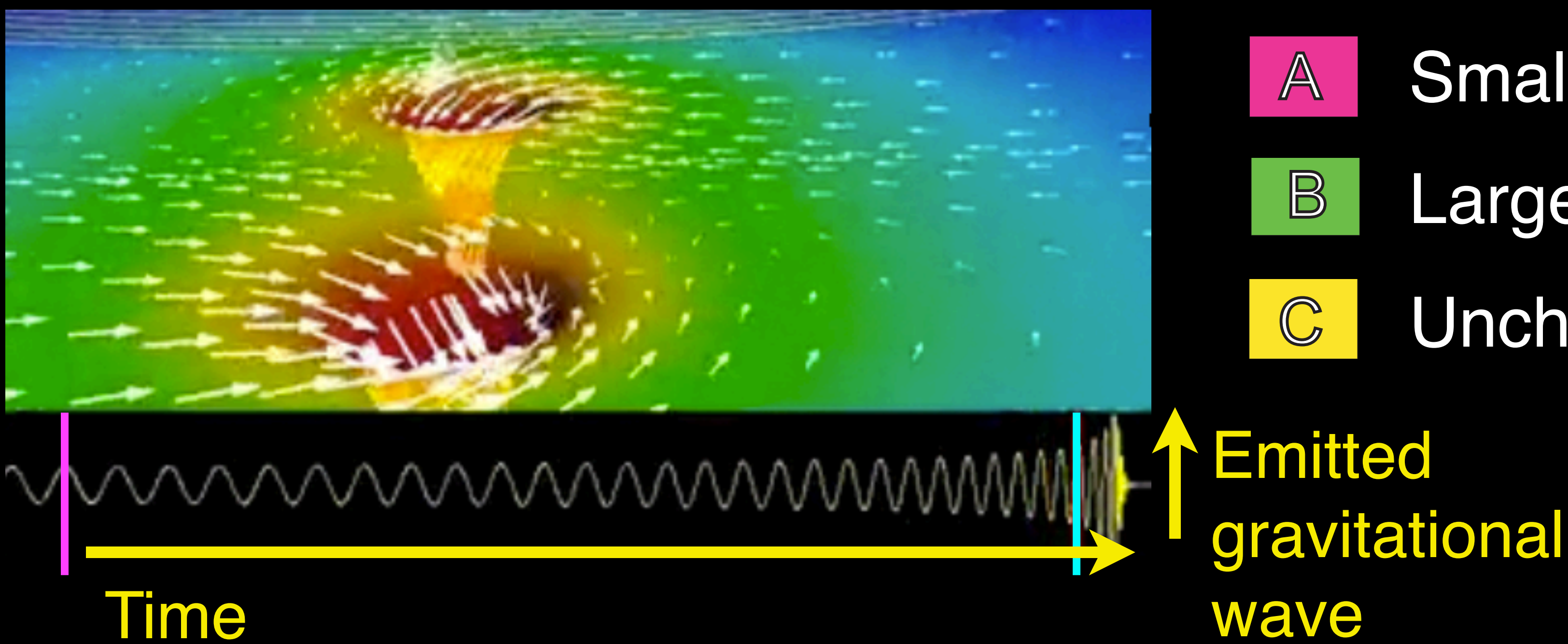
A Smaller

B Larger

C Unchanged

Clicker question #129

- The graph below shows what a detector would observe as a gravitational wave from two merging black holes went by. Compared to the earlier time, at the current time shown, the gravitational-wave **period** is

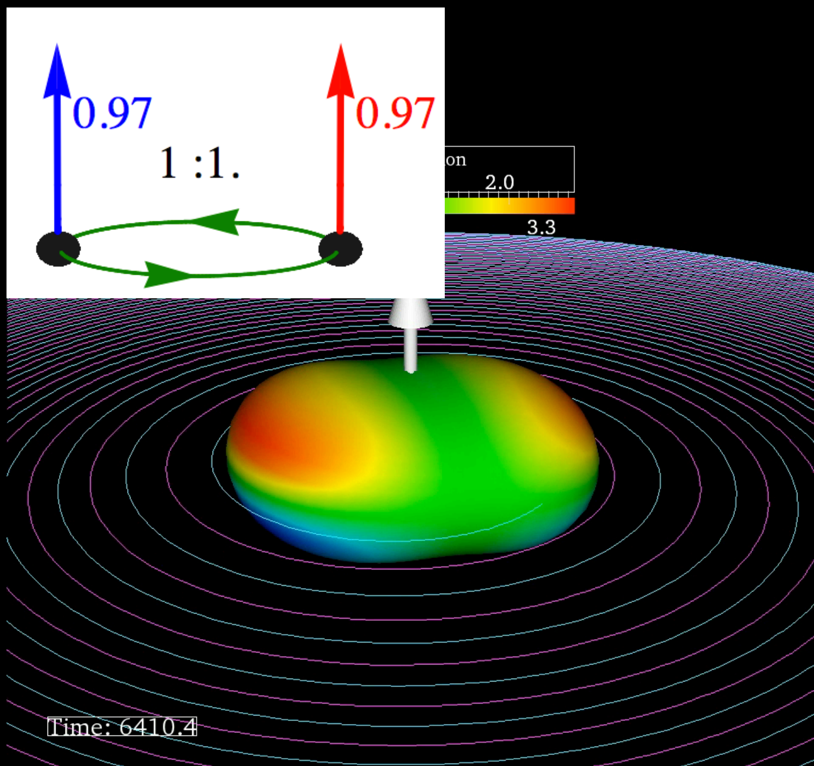


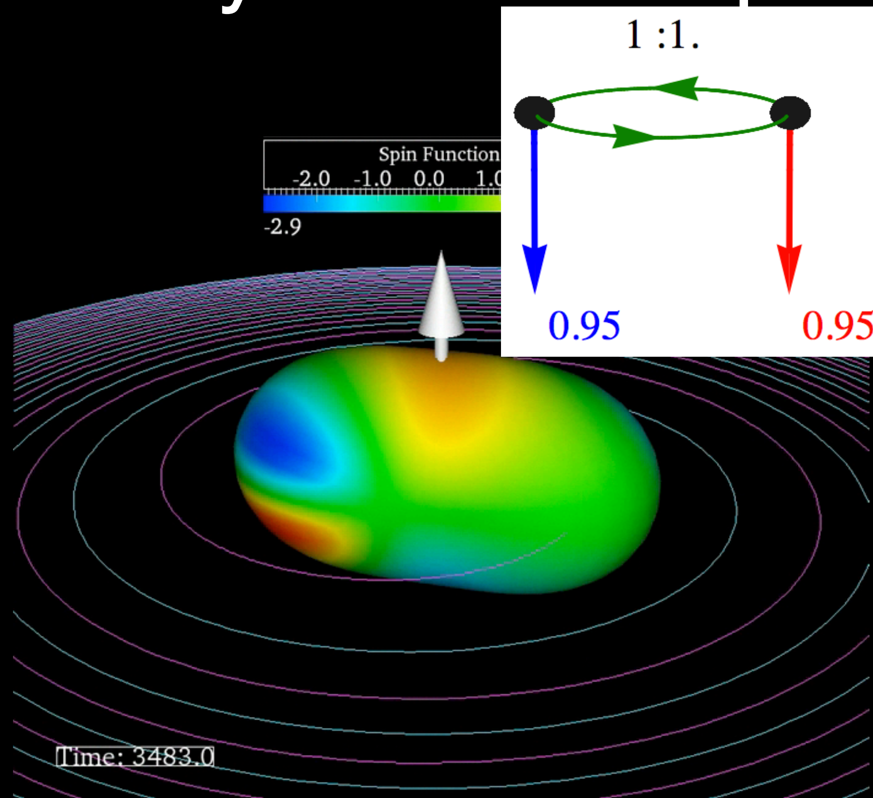
A Smaller

B Larger

C Unchanged

BH-BH mergers with nearly extremal spin





25.5 orbits

11% of initial mass radiated

$\chi_{\text{final}} = 0.945$

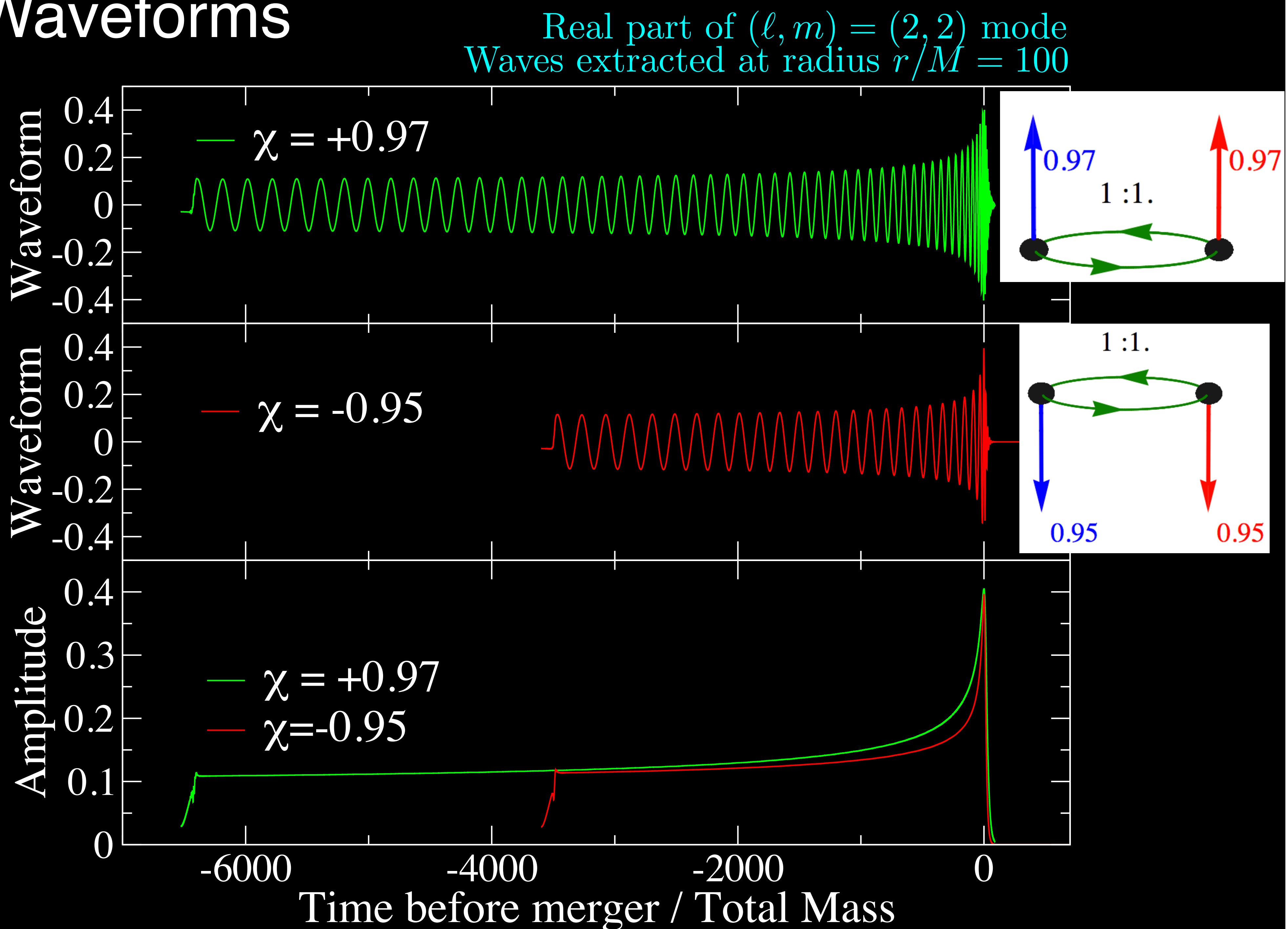
12.5 orbits

3% of initial mass radiated

$\chi_{\text{final}} = 0.376$

See GL, M. Boyle, M. A. Scheel, B. Szilágyi (2012), arXiv:1110.2229 for details.

Waveforms



Real part of $(\ell, m) = (2, 2)$ mode
Waves extracted at radius $r/M = 100$
Waveform
χ = +0.97
0.97
0.97
1 :1.
Waveform
χ = -0.95
1 :1.
0.95
0.95
Amplitude
χ = +0.97
χ=-0.95
0.4
0.2
0
-0.2
-0.4
0.3
0.1
-6000
-4000
-2000
0
Time before merger / Total Mass

GWPAC GRAVITATIONAL WAVE Physics and Astronomy Center

CALIFORNIA STATE UNIVERSITY FULLERTON

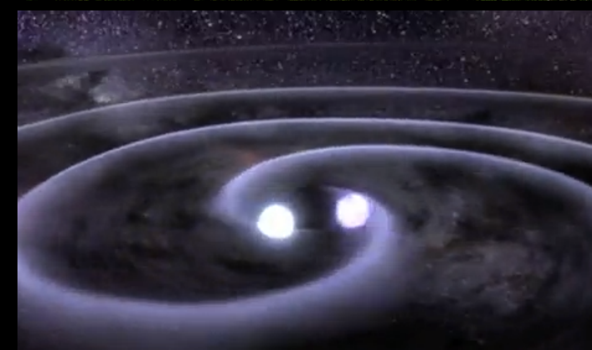
- Research at CSUF GWPAC

  - Joshua Smith
    - Gravitational-wave (GW) experiment

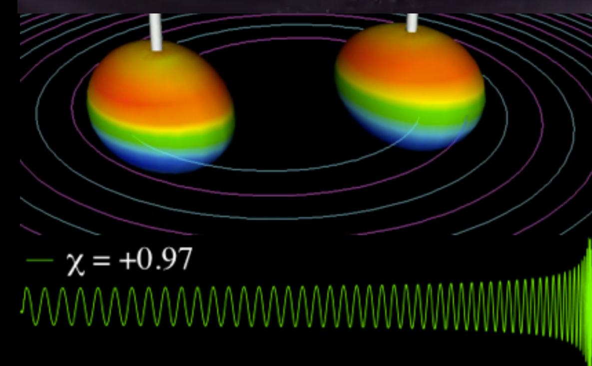
  - Jocelyn Read
    - Theory of neutron stars, a primary source of GWs

  - Geoffrey Lovelace
    - Simulate GWs from merging black holes & neutron stars

Source: LIGO



Source: NASA/Goddard



- Want to learn more?
  - Take PHYS 120 “Introduction to Astronomy”
  - http://physics.fullerton.edu/gwpac (or drop by MH-601)

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Followup: likes & dislikes

- Like about the class
  - 50% demos/real-world examples/video clips
  - 32% worked examples
  - 8% exam format/policy
  - 6% lecture style
- Dislike about the class
  - 24% nothing
  - 18% pacing
  - 8% Mastering Physics
  - 8% Worked examples too fast/too few

Followup: clock pendulum

- 0. Full name
- 1. **Question 13.9 Grandfather Clock**

A grandfather clock has a weight at the bottom of the pendulum that can be moved up or down. If the clock is running slow, what should you do to adjust the time properly?

$$T = 2\pi\sqrt{\frac{l}{g}}$$

A 64% move the weight up

B 25% move the weight down

C 8% moving the weight will not matter

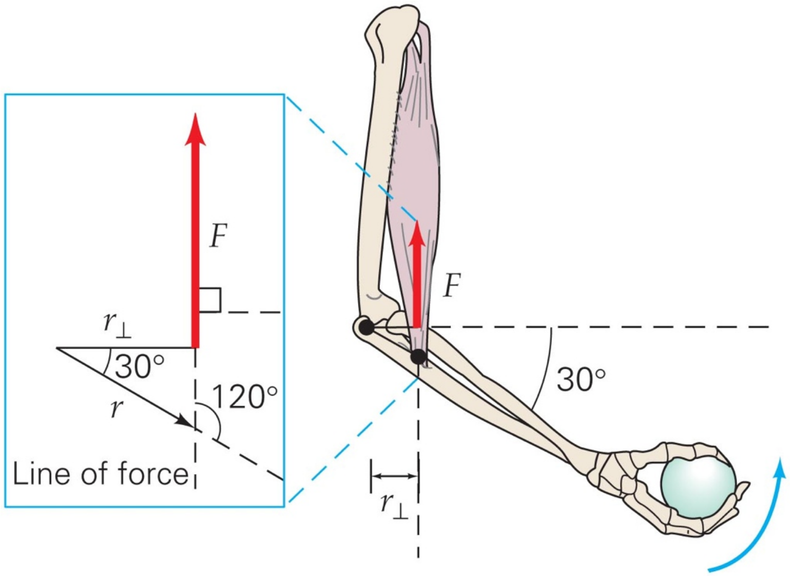
D 2% call the repairman

Followup: most anxious

- 61% Rotational motion
  - 18% In general / all of it
  - **17% Torque**
  - 8% angular velocity
- 15% Waves
  - Will wrap up today
- 15% Simple harmonic motion
  - Covered on homework #11...please stop by office hours if you have questions

Ex. 8.2: lifting

Muscle applies a force of 600 N at a point 4cm from the elbow joint as shown. What is the torque?



(a) Starting to lift

Given:

$$F = 600 \text{ N}$$

$$r = 4 \text{ cm}$$

$$\theta_{rF} = 120°$$

Goal: $\vec{\tau}$

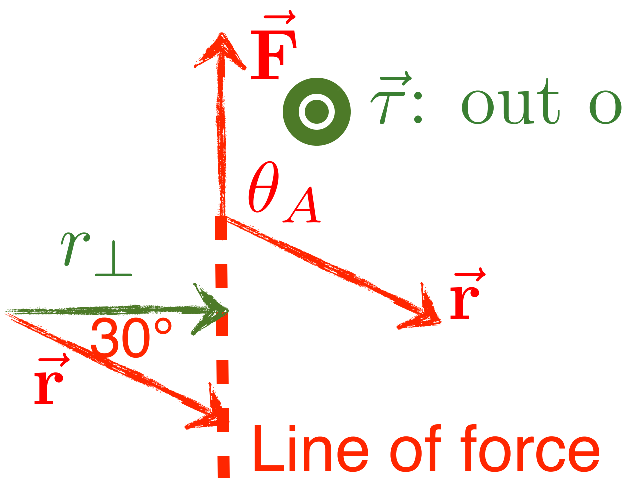
Principle: torque

$$\tau = r_\perp F = rF \sin\theta_{rF}$$

Direction: Right-hand rule

Ex. 8.2: lifting

Muscle applies a force of 600 N at a point 4cm from the elbow joint. What is the torque in each case?



$\vec{\tau}$: out of page

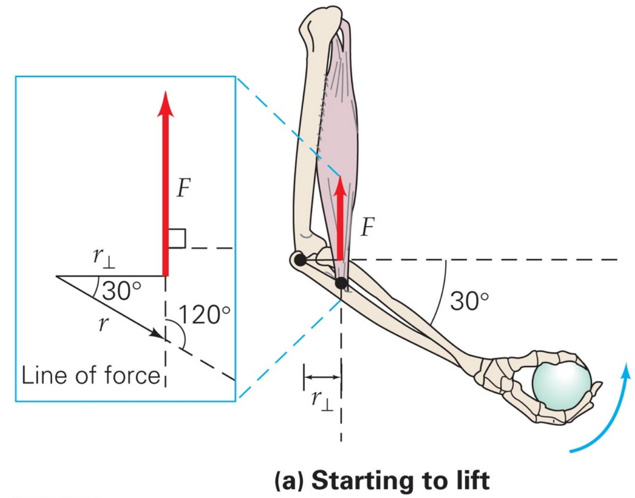
Given:

$$F = 600 \text{ N}$$

$$r = 4 \text{ cm}$$

$$\theta_A = 120^\circ$$

Goal: $\vec{\tau}$



(a) Starting to lift

$$\tau = r_\perp F = rF\cos 30^\circ = rF\sin 120^\circ$$

$$\tau = rF\sin\theta_{rF} = rF\sin 120^\circ$$

$$\tau = (4 \text{ cm})(600 \text{ N})\sin 120^\circ = 21 \text{ m}\cdot\text{N}$$

$\vec{\omega}$: out of page

$\vec{\alpha}$: out of page

$$\vec{\tau} = I\vec{\alpha}$$

Final class participation

- 0. Full name
- 1. The coolest thing you learned in this course

Thank you for being a wonderful class!
Good luck on your finals and enjoy the break.