4.4 The Force of Gravity

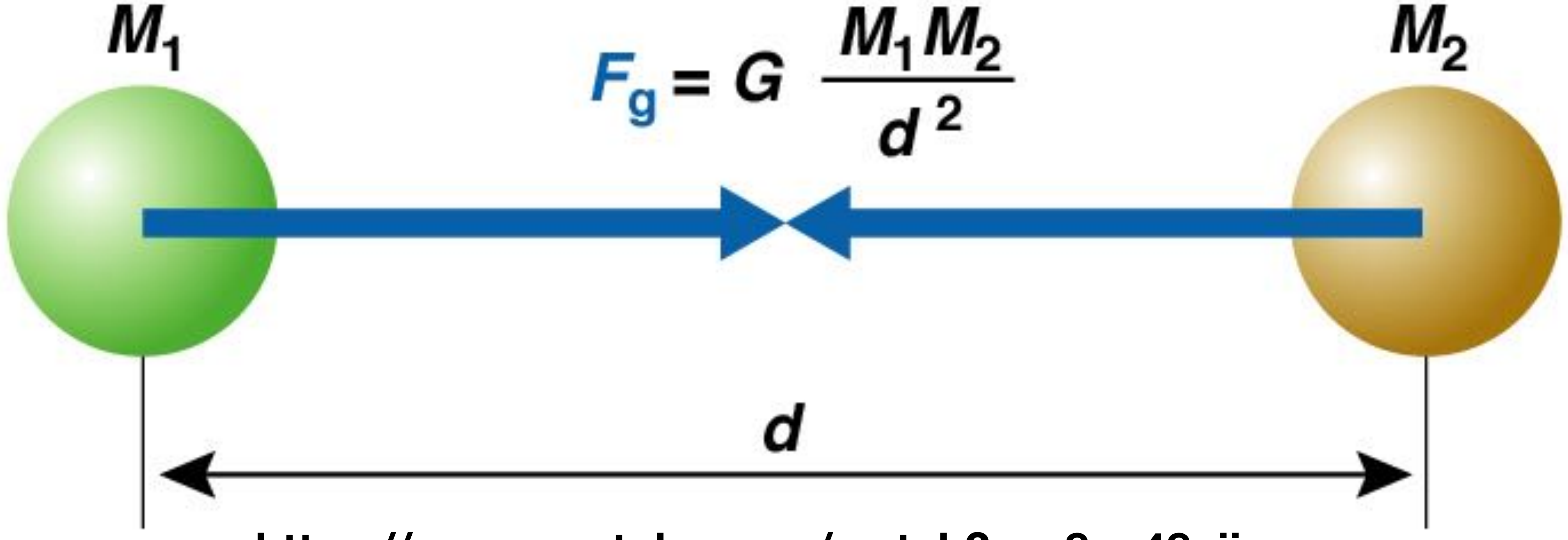
Our goals for learning:

- What determines the strength of gravity?
- How does Newton's law of gravity extend Kepler's laws?
- How do gravity and energy together allow us to understand orbits?
- Why are large objects spherical?
- How does gravity cause tides?

What determines the strength of gravity?

The **Universal Law of Gravitation:**

1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.

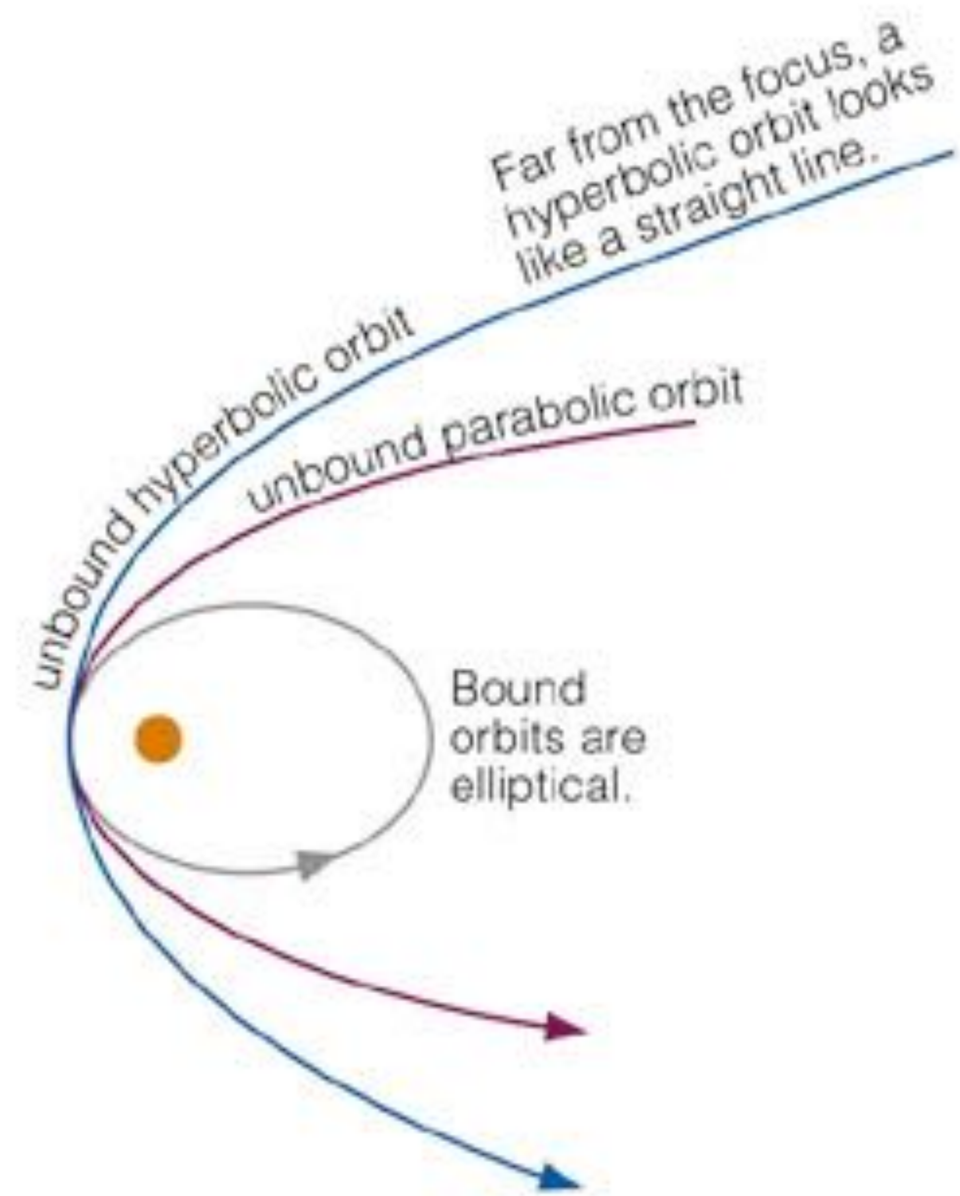


https://www.youtube.com/watch?v=y8zg48aijmo

How does Newton's law of gravity extend Kepler's laws?

- Kepler's first two laws apply to all orbiting objects, not just planets.

- Ellipses are not the only orbital paths. Orbits can be:
  - — bound (ellipses)
  - — unbound
    - parabola
    - hyperbola



Newton's version of Kepler's Third Law

$$P^2 = \frac{4\pi^2}{G}\frac{a^3}{M}$$

p = orbital period

a = average orbital distance (between centers)

$(M_1 + M_2)$ = sum of object masses

(e.g., the mass of the sun)

derive

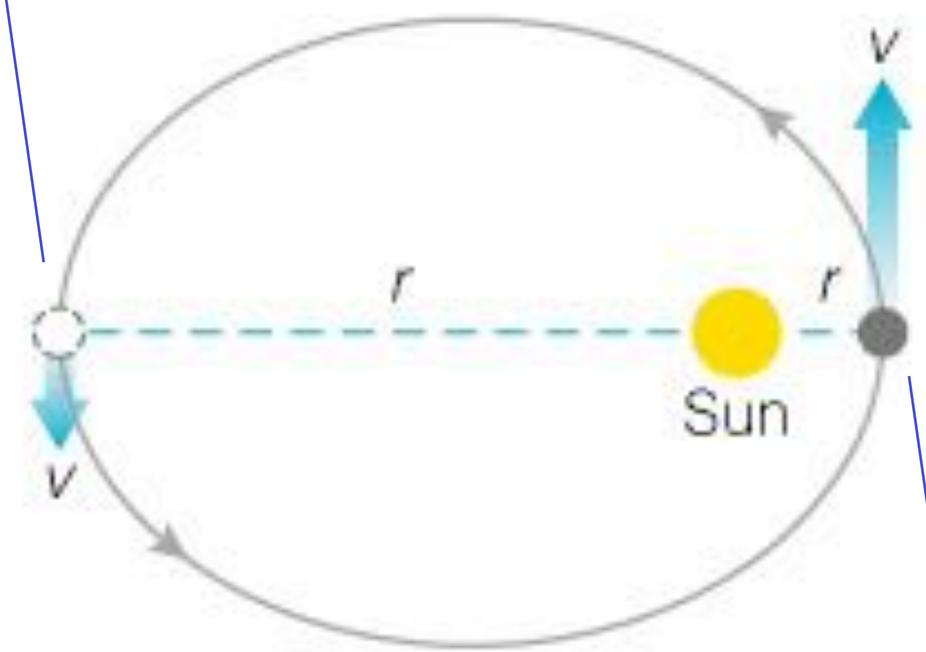
Orbits of the Moons of Jupiter

Moon	P (days)	a (km)	a^3/P^2 (solar masses)
Io	1.8	4×10^5	0.001
Europa	3.6	7×10^5	0.001
Ganymede	7.2	1×10^6	0.001
Callisto	16.7	2×10^6	0.001

The moons of Jupiter obey a scaled version of Kepler's Third Law

How do gravity and energy together allow us to understand orbits?

More gravitational energy;
Less kinetic energy



Less gravitational energy;
More kinetic energy

Total orbital energy stays constant.

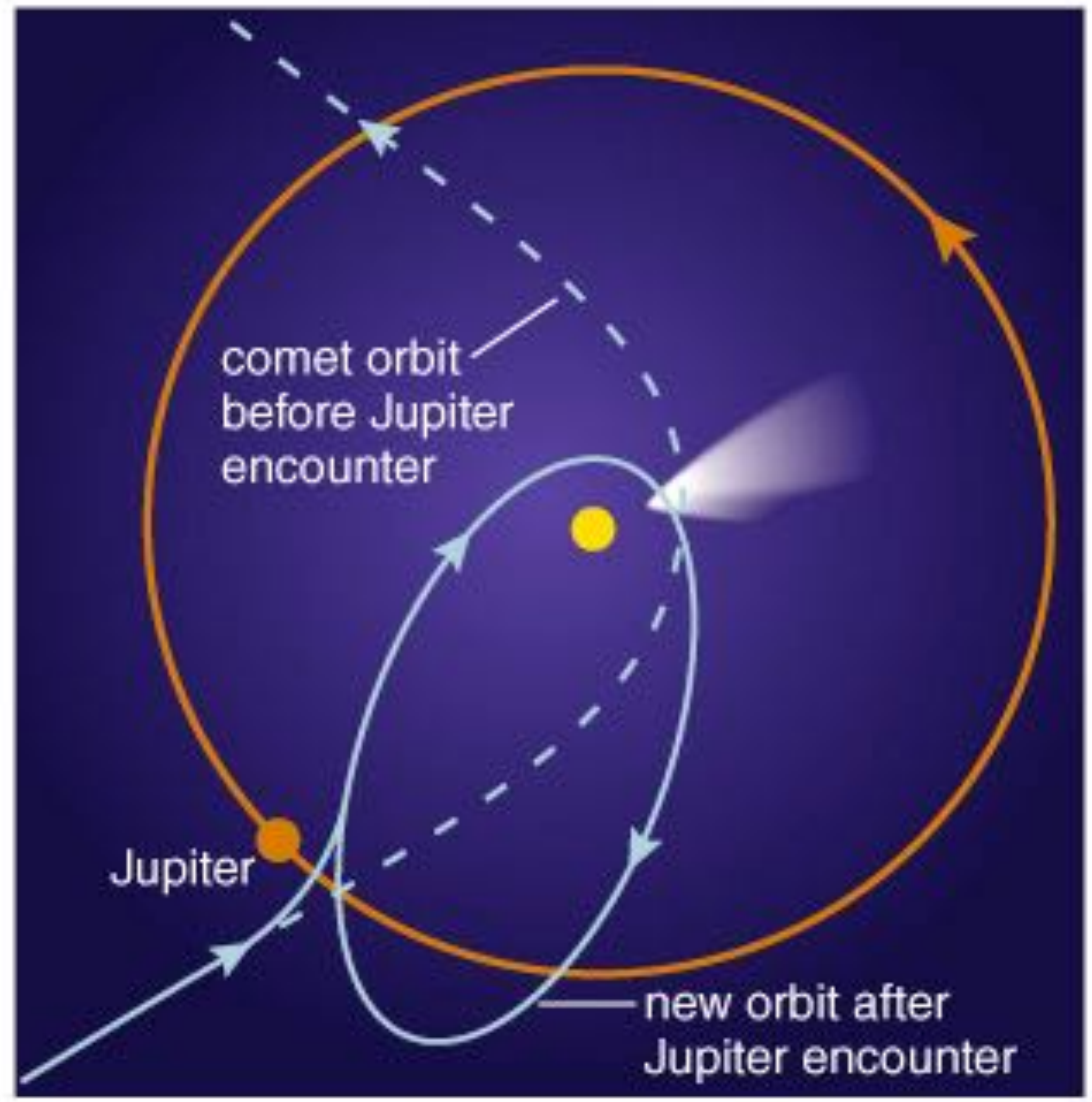
- Total orbital energy (gravitational + kinetic) stays constant if there is no external force.
- Orbits cannot change spontaneously.

Changing an Orbit

⇒ So what can make an object gain or lose orbital energy?

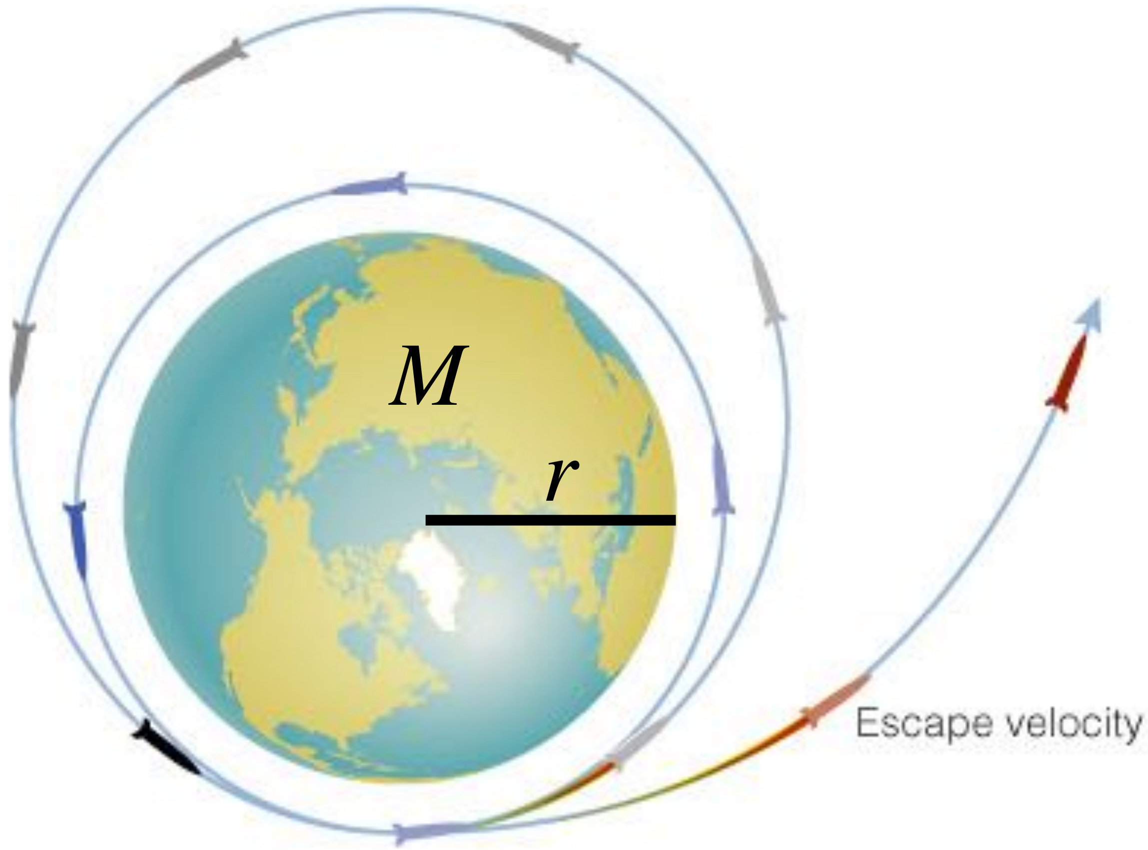
- Friction or atmospheric drag
- A gravitational encounter
- The thrust of a rocket

i.e., some external force



movie: Messenger orbit **https://www.youtube.com/watch?v=GXEuQtpreXE**

Escape Velocity



- If an object gains enough orbital energy, it may escape (change from a bound to unbound orbit).
- **Escape velocity** from Earth ≈ 11 km/s from sea level (about 40,000 km/hr).

Circular & Escape velocity

Circular velocity: $$v_{circ} = \sqrt{\frac{GM}{r}}$$

Escape velocity: $$v_{esc} = \sqrt{\frac{2GM}{r}} = \sqrt{2}v_{circ}$$

Examples:

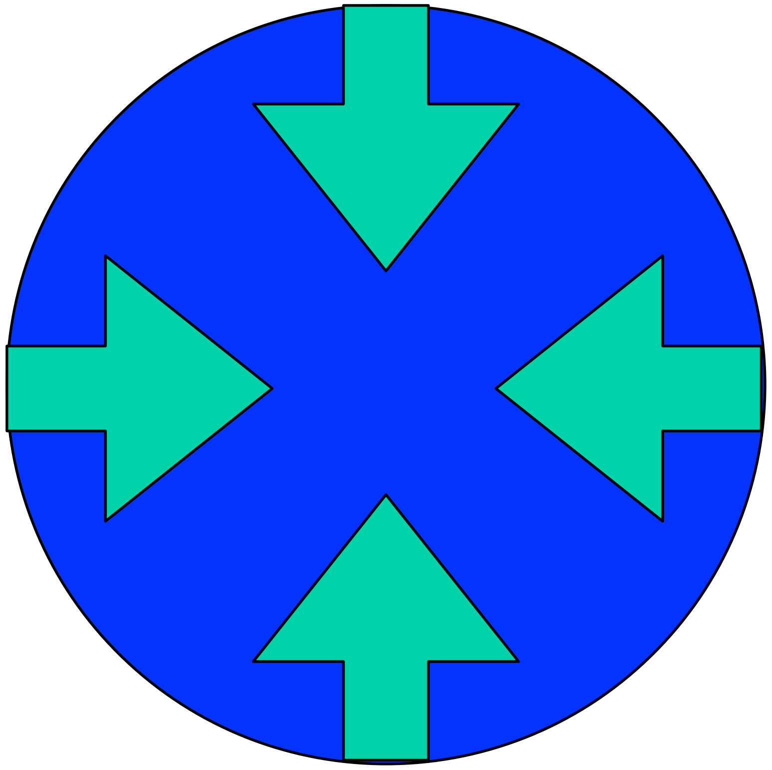
Object	circular speed at surface	escape speed from surface
Earth	7.8 km/s	11 km/s
Sun	436 km/s	617 km/s
Moon	1.7 km/s	2.4 km/s

What have we learned?

- What determines the strength of gravity?
  - Directly proportional to the *product* of the masses (M × m)
  - *Inversely* proportional to the *square* of the separation
- How does Newton's law of gravity allow us to extend Kepler's laws?
  - Applies to other objects, not just planets
  - Includes unbound orbit shapes: parabola, hyperbola as well as bound ellipse (all conic sections)
  - Can be used to measure mass of orbiting systems

Why are stars and planets spherical?

- Gravity pulls - it is an attractive force
- IF self-gravity is the most important force holding an object together, it must be spherical.



Example: Earth

- Diameter of Earth: 12,756 km
- Mt. Everest: 8.848 km above sea level
- Marianas Trench: 10.934 km below
- Maximum variation: 19.782 km

$$\frac{\text{maximum variation}}{\text{diameter}} = \frac{19.782}{12,756}$$

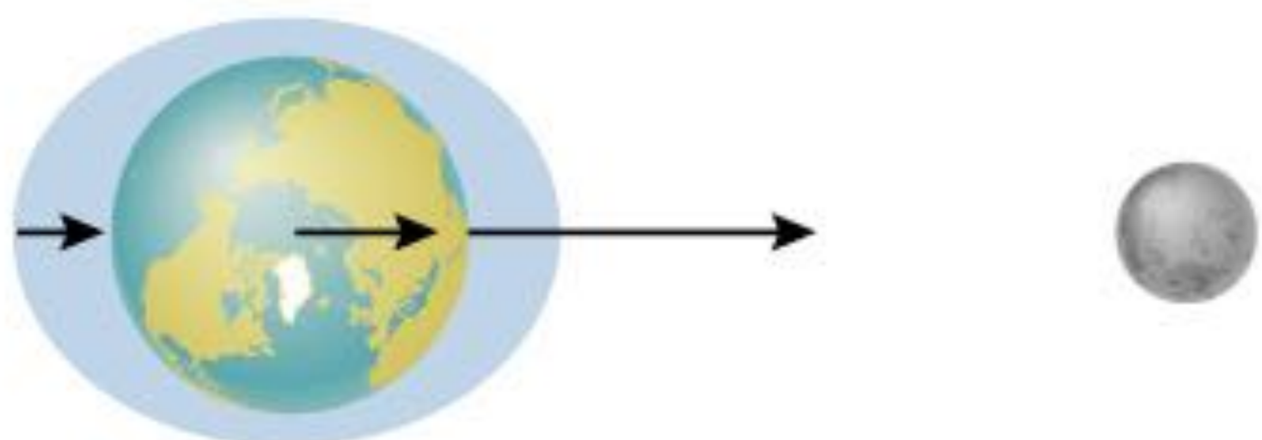
$$= 0.0015$$

- a very smooth sphere!

- Gravity makes individual objects round
  - about 100 km in diameter is where objects start to become dominated by self-gravity
    - planets round
    - asteroids still lumpy

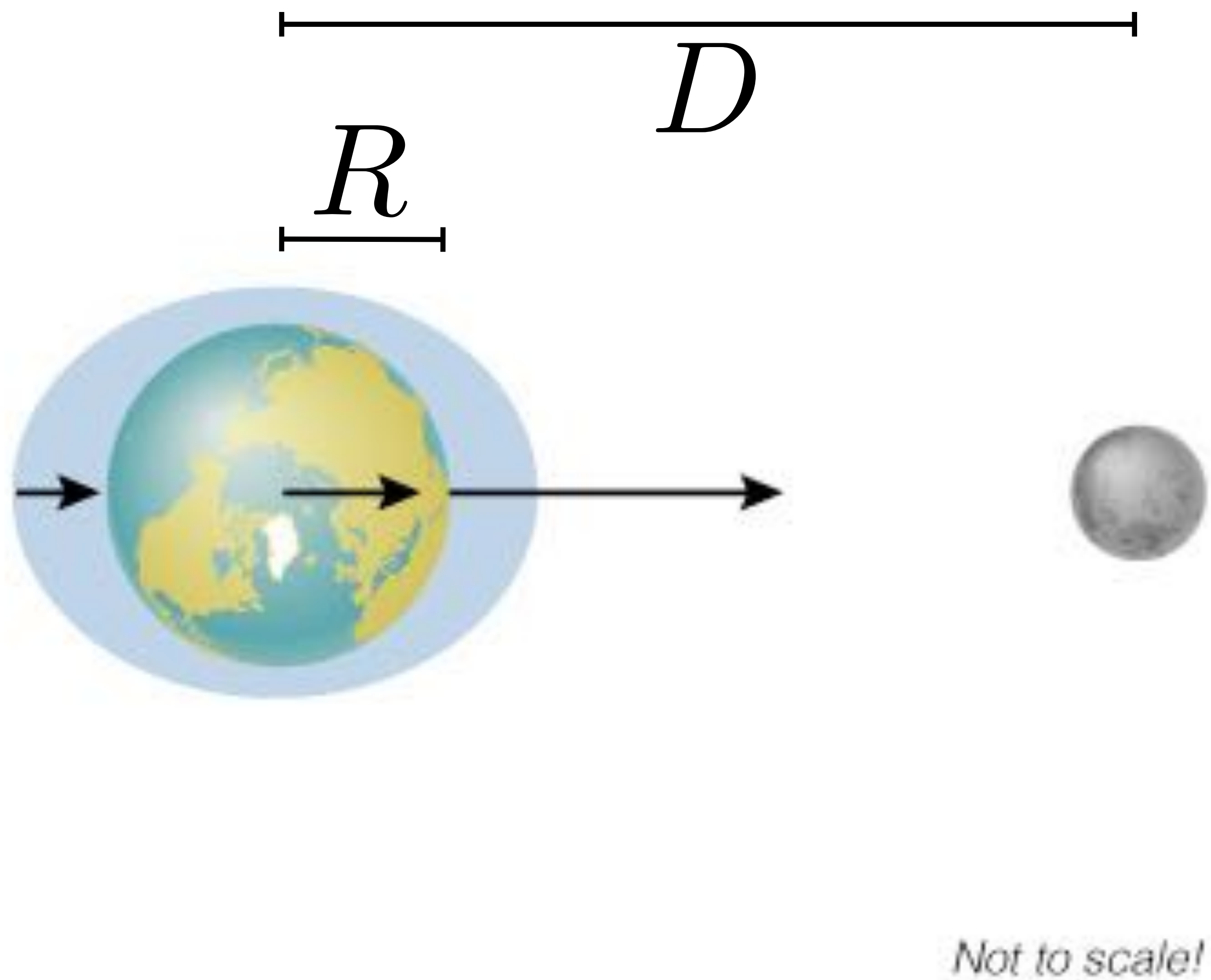
This holds for individual objects.
What about multiple objects?

Tides



Tides are the result of differential gravity

- The Moon's gravity pulls harder on near side of Earth than on far side (inverse square law).
- The difference in the Moon's gravitational pull stretches Earth.



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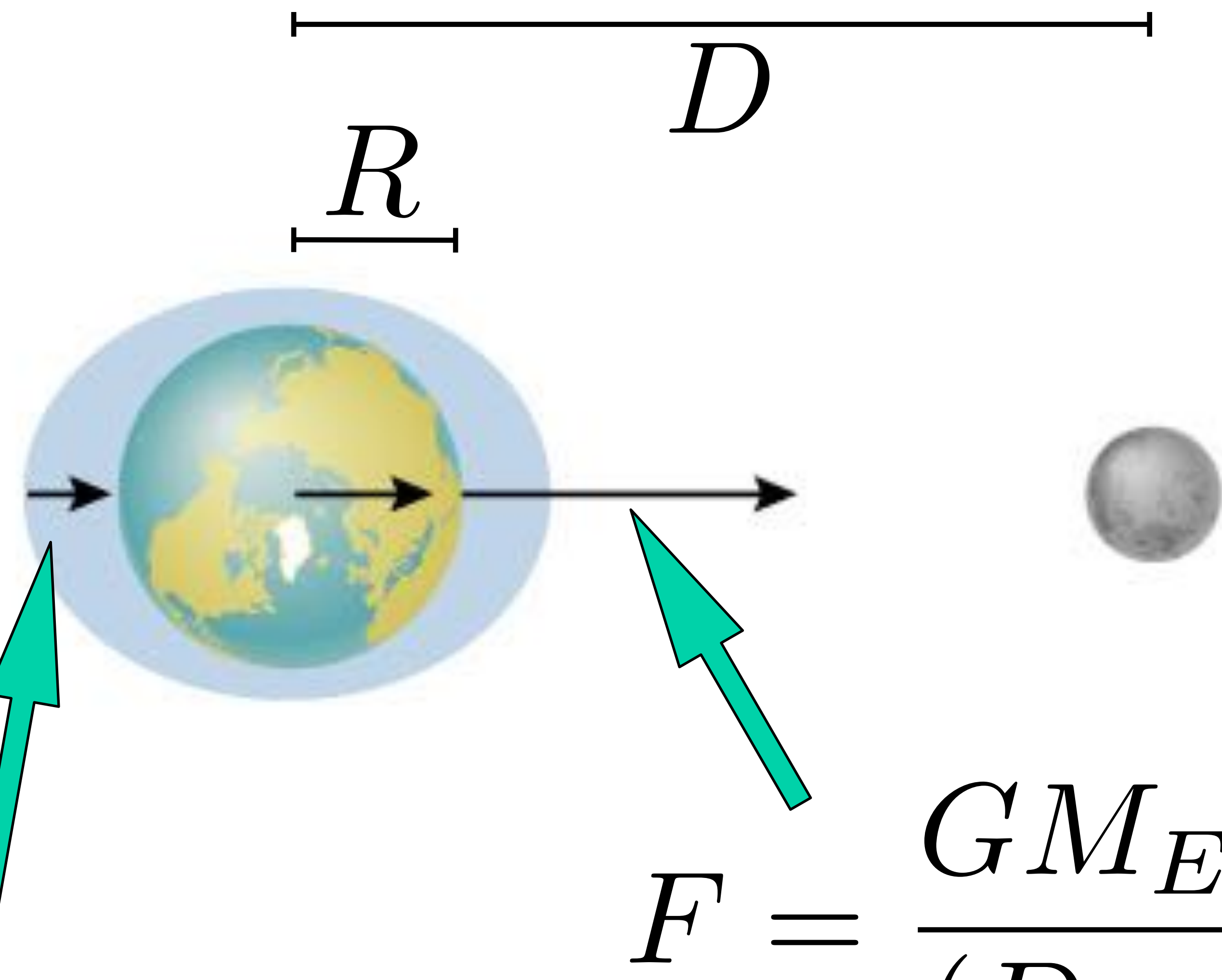


$$F = \frac{GM_E M_m}{(D-R)^2}$$

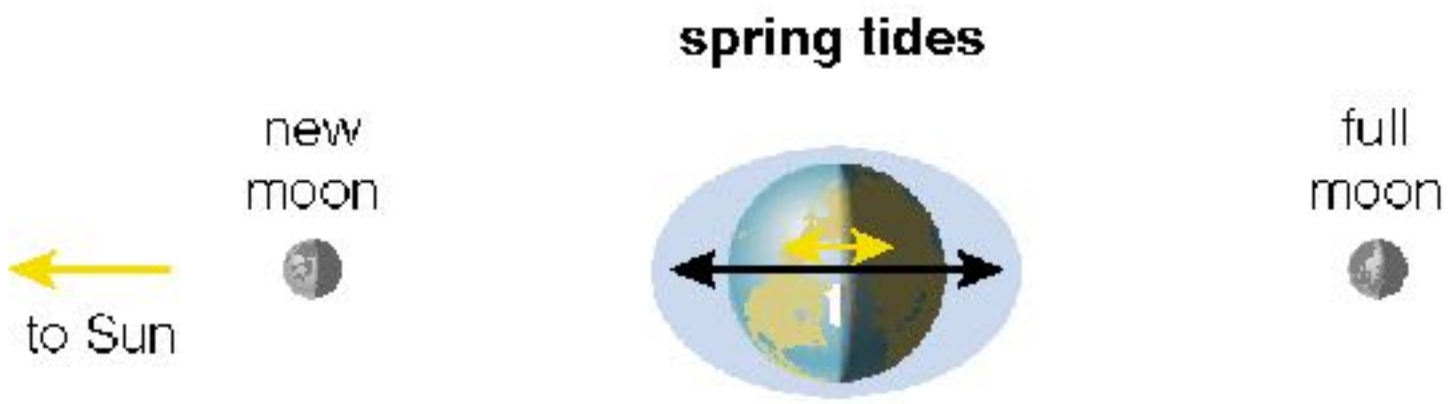
$$F = \frac{GM_E M_m}{(D+R)^2}$$

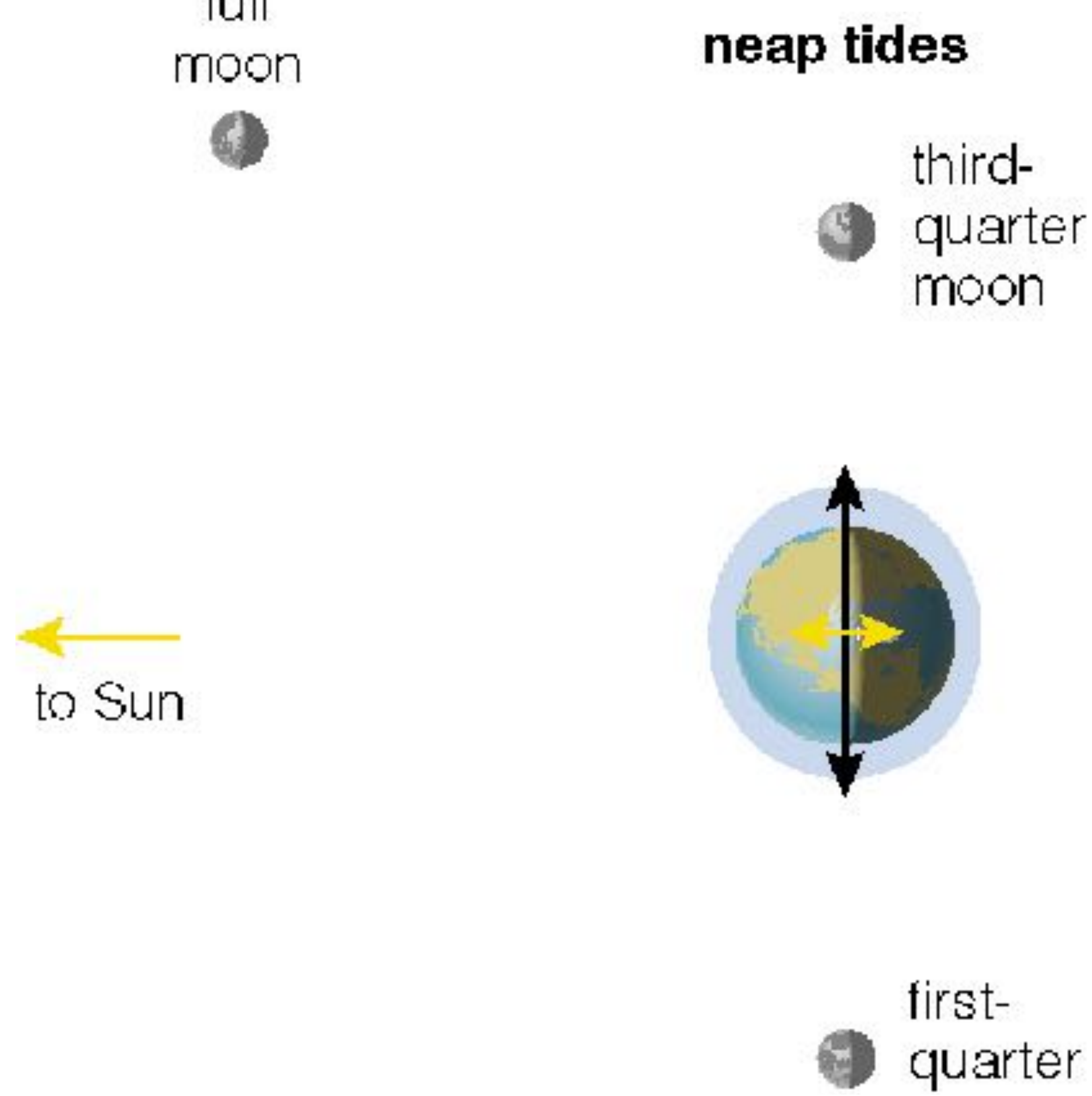
$$D = 384,400 \text{ km}$$

$$R = 6,378 \text{ km}$$

So the gravitational attraction towards the moon is about 7% stronger on the near side of the Earth than on the far side.

Tides and Phases



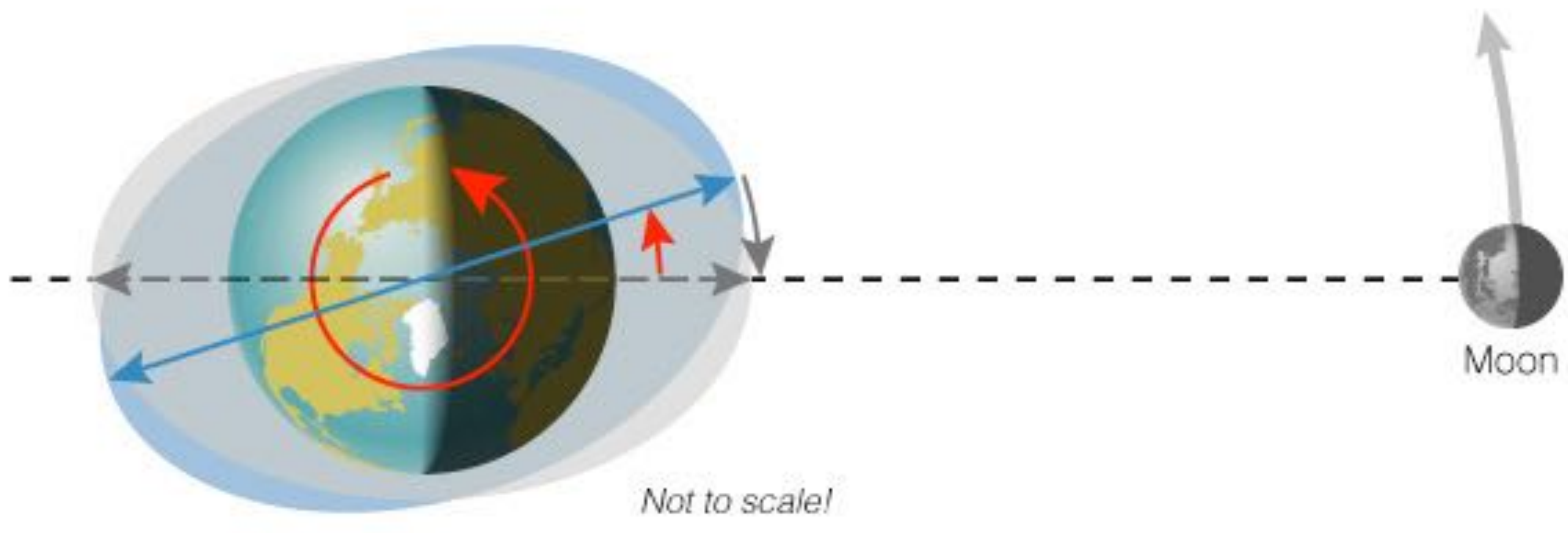


Size of tides depends on the phase of the Moon.

Spring tides are stronger than neap tides because the sun and moon team up at new & full moon.

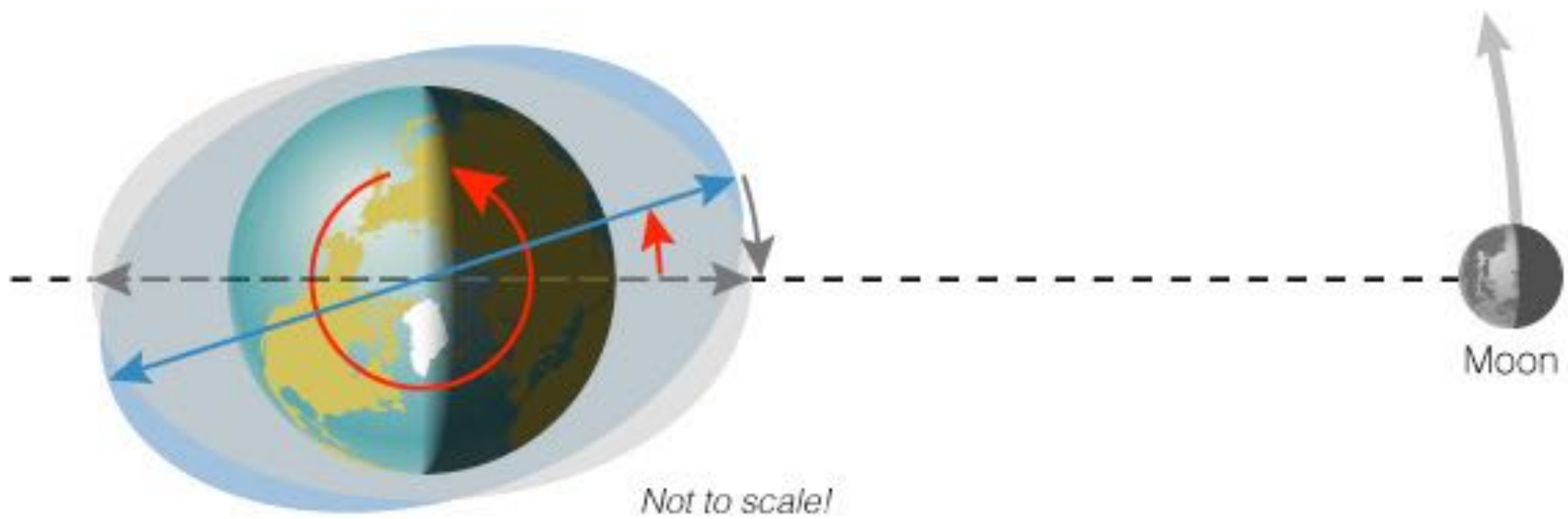
https://www.youtube.com/watch?v=l37ofe9haMU

Tidal Friction



- The spin of the Earth drags the tidal bulge of the ocean ahead of the ideal oblate spheroid, which is aligned with the moon.
- The gravity of the moon pulls back on the leading, near side bulge more strongly than it pulls forward the far side bulge.
- The net result is **tidal friction**, which results in a gradual braking of the spin of the Earth.

Tidal Friction



- Tidal friction gradually slows Earth rotation
  - Moon gradually drifts farther from Earth (3.8 centimeters per year)
  - conservation of angular momentum

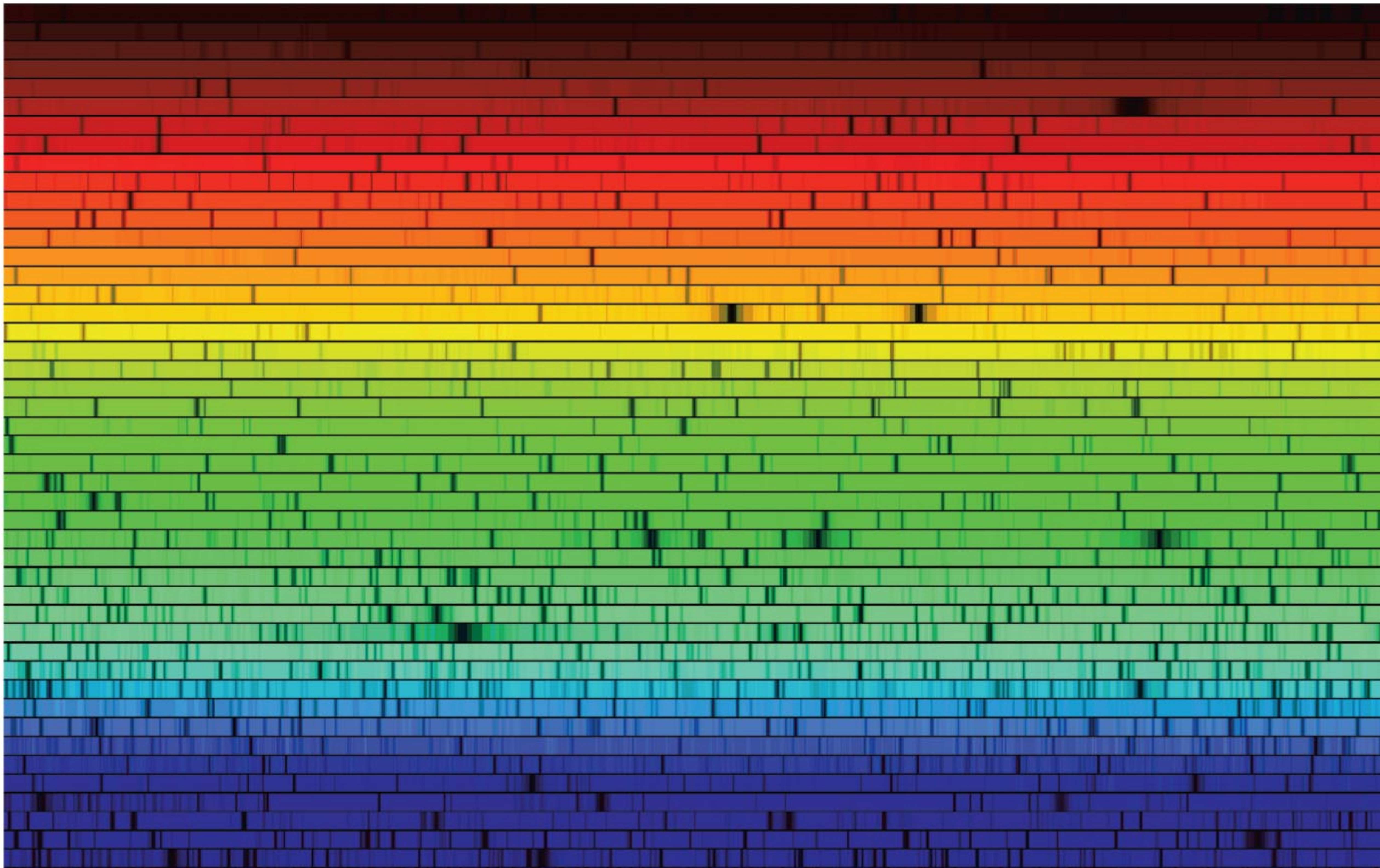
The length of Earth’s day increases 2 milliseconds per century

- Moon once spun faster; tidal friction caused it to “lock” in synchronous rotation
  - orbit period:spin period = 1:1

Summary of Tides

- Gravitationally bound objects are spherical
  - e.g., planets, stars
- Tides are caused by the differential gravity of the sun and moon
  - Spring tides are cause when the sun and moon are aligned; neap tides when they are perpendicular.
- Tidal friction gradually changes
  - the orbit of the moon and the spin of the earth

Electromagnetic Radiation



Electromagnetic Radiation

aka Light

“Radiation” sounds scary, but there are many benign forms of radiation - including visible light, radio waves, and infrared radiation.

These are all fundamentally the same stuff.

Electromagnetic Radiation

aka Light

- Properties of Light are simultaneously
  - **wave-like** AND
  - **particle-like**

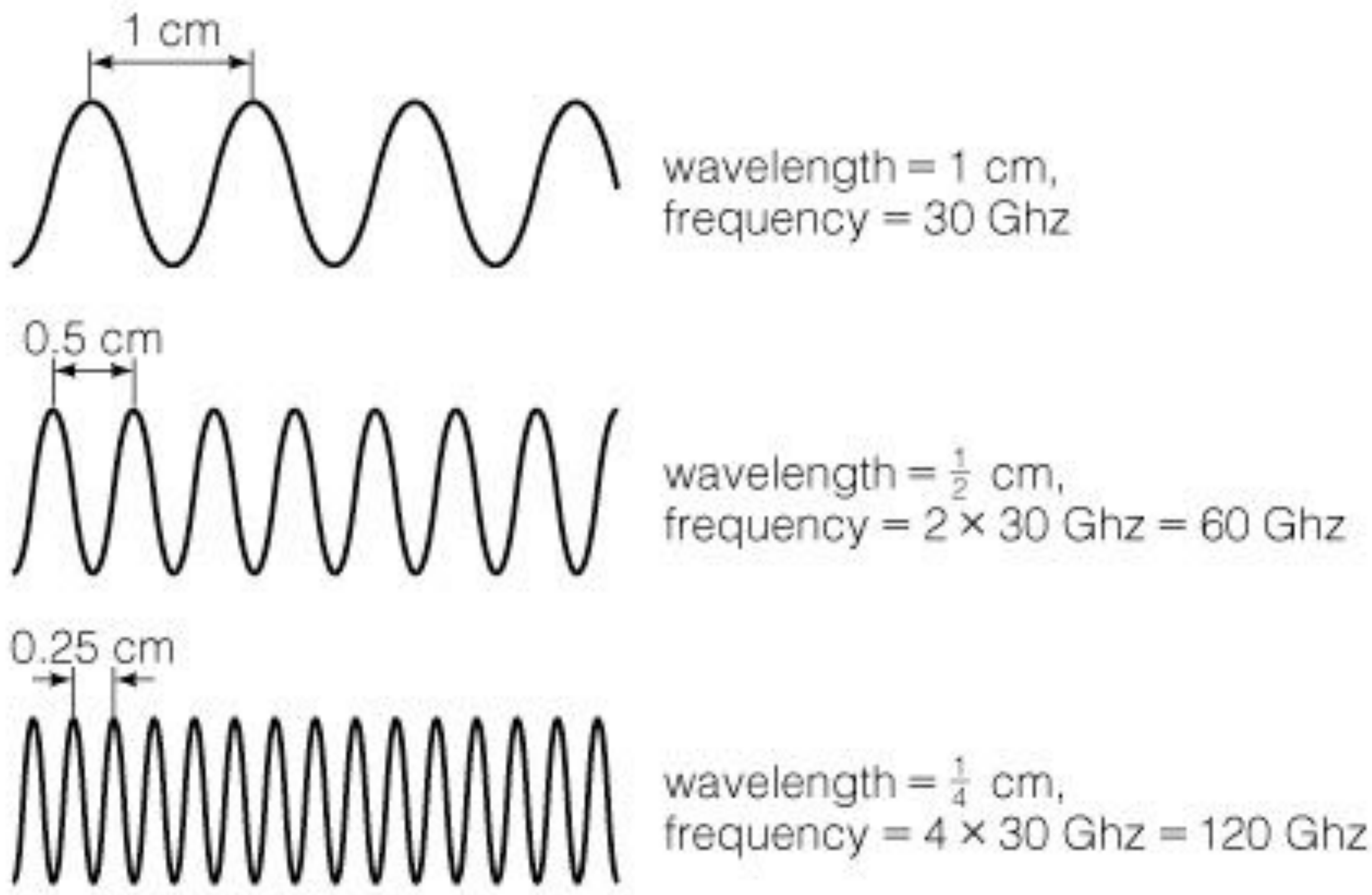
Sometimes it behaves like ripples on a pond (waves).
Sometimes it behaves like billiard balls (particles).

Called the "wave-particle" duality in quantum mechanics.

Particles of Light

- Particles of light are called **photons.**
- Each photon has a wavelength and a frequency.
- The energy of a photon depends on its frequency.

Wavelength and Frequency



Wavelength & Frequency

λ = wavelength (separation between crests)

f = frequency (rate of oscillation)

c = speed of light = 3×10^8 m/s

$$\lambda f = c$$

Wavelength, Frequency, and Energy

photon energy:

$$E = hf = hc/\lambda$$

$$h = 6.626 \times 10^{-34} \text{ joule} \times \text{s}$$

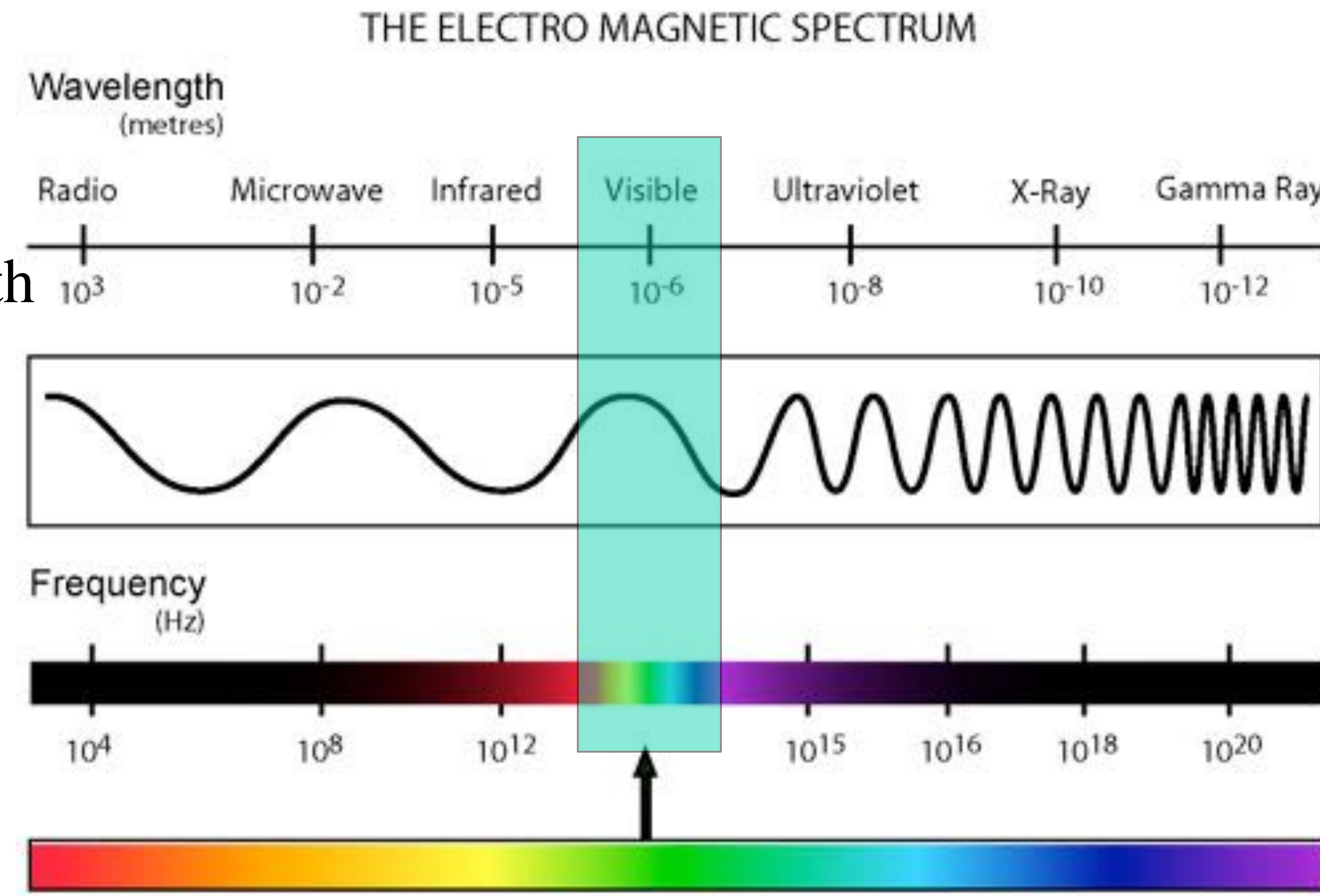
(Planck's constant)

The frequency *f* can be arbitrarily high or low, so the energy carried by an individual photon can be arbitrarily high or low. However, the energy always comes in a finite unit of one photon at a time, not continuously.

Long wavelength

Low energy

Low frequency



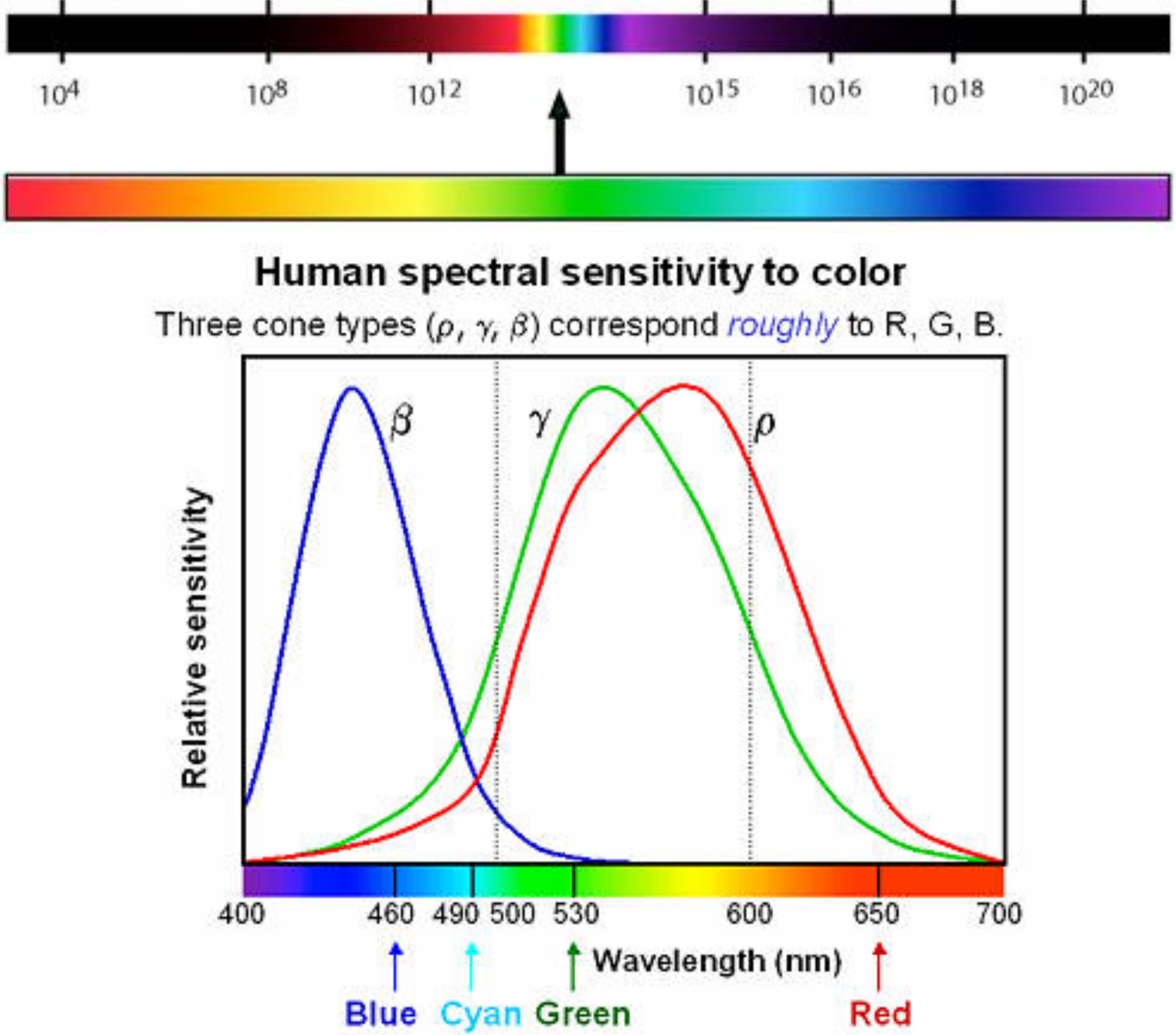
Short wavelength

High energy

High frequency

$E\ ,f\ \ increasing$

$\lambda\ decreasing$



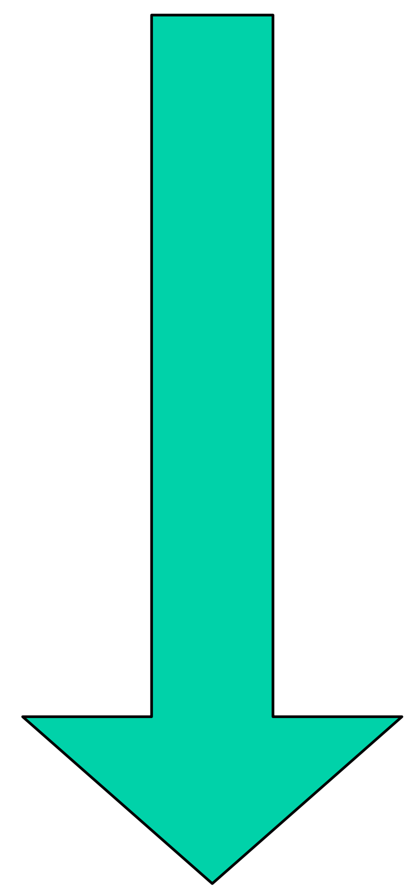
Our eyes are only sensitive to a factor of two range in wavelength, from 380nm (violet) to 700nm (deep red).

Same stuff, different Energy:

Electromagnetic Radiation

- Radio
- microwave
- infrared
- visible light
- ultraviolet
- X-ray
- gamma ray

Energy per photon increasing



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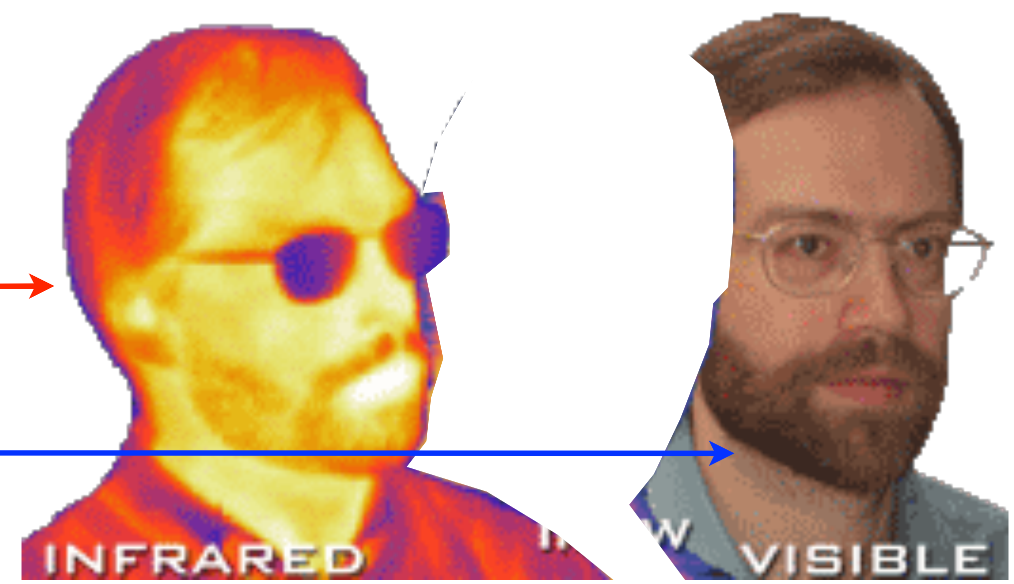

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