What is Matter?

A Classical Introduction
to the
Physical Universe

by
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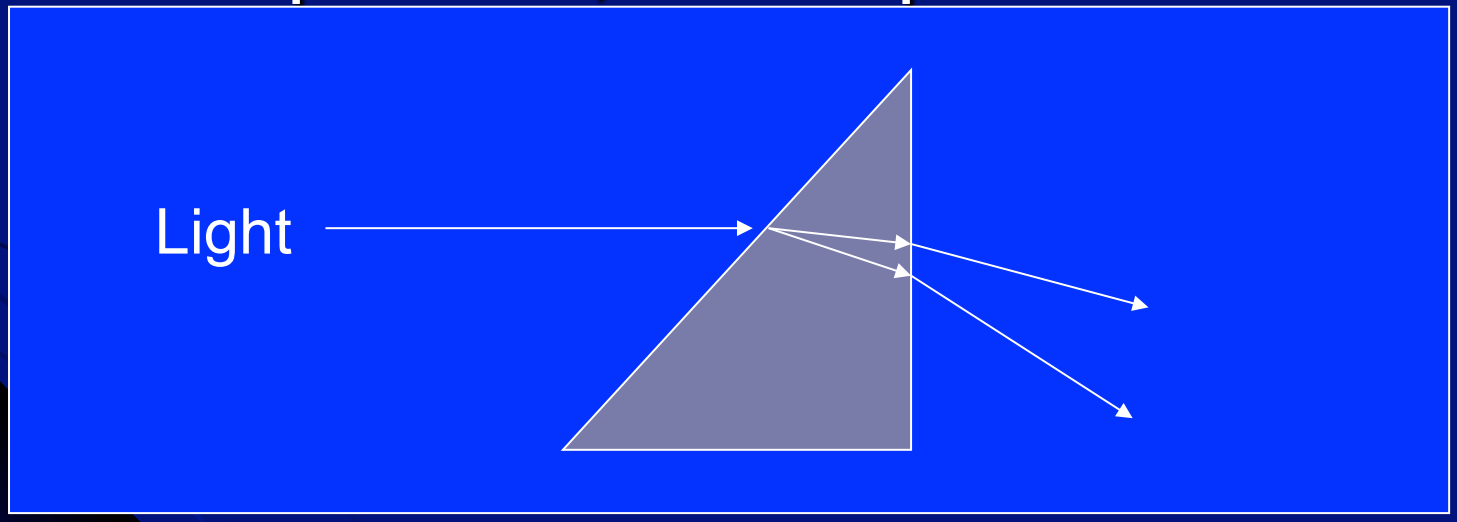
Early Theories of Light

- Early theories of light were based on analogy with sound waves. The medium of propagation was called the ‘luminous aether’. Nowadays it is called ‘the vacuum’ or ‘empty space’ to emphasize that it is not made of matter.

Polarization

- 1600's: Christian Huygens used birefringent crystals to separate light into two components, called 'polarizations'.



- Light polarization is easily demonstrated using polarizers.

Light: Waves or Particles?

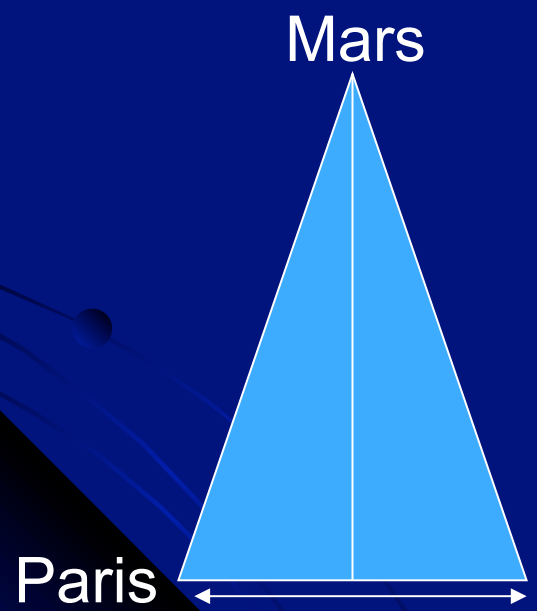
- 1600's: Isaac Newton observed a similarity between colors of light and tones of sound but criticized the wave theory of light because sound waves do not have two polarizations. He thought that light might consist of particles which could have different orientations.

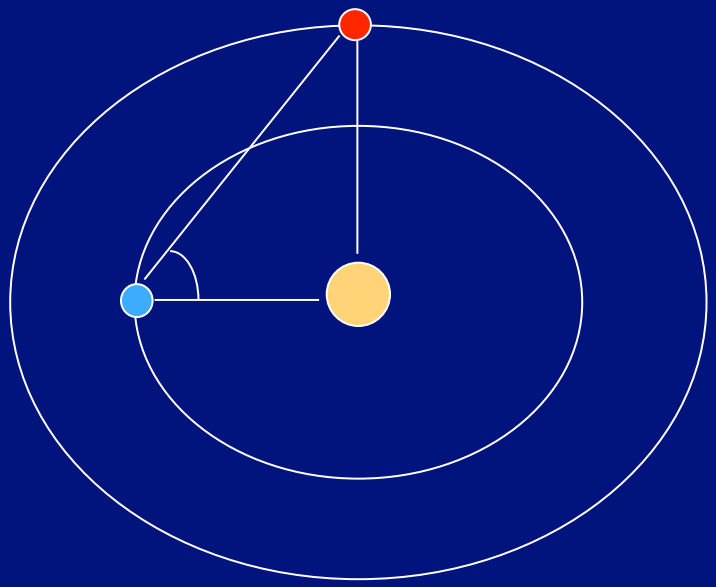
Speed of Light

- 1675: Olaf Roemer observed that the time between eclipses of the first moon of Jupiter (moon moving behind Jupiter) lengthened as Earth and Jupiter moved farther apart. He deduced that it takes light 11 minutes (actually about 8 min 20 sec) to travel between the Sun and Earth.

Cassini

- 1672: Giovanni Domenico Cassini measured the Earth-Sun distance to be 140,000,000 km using parallax methods.





Speed of Light

- From Roemer's and Cassini's measurements the speed of light can be calculated to be:

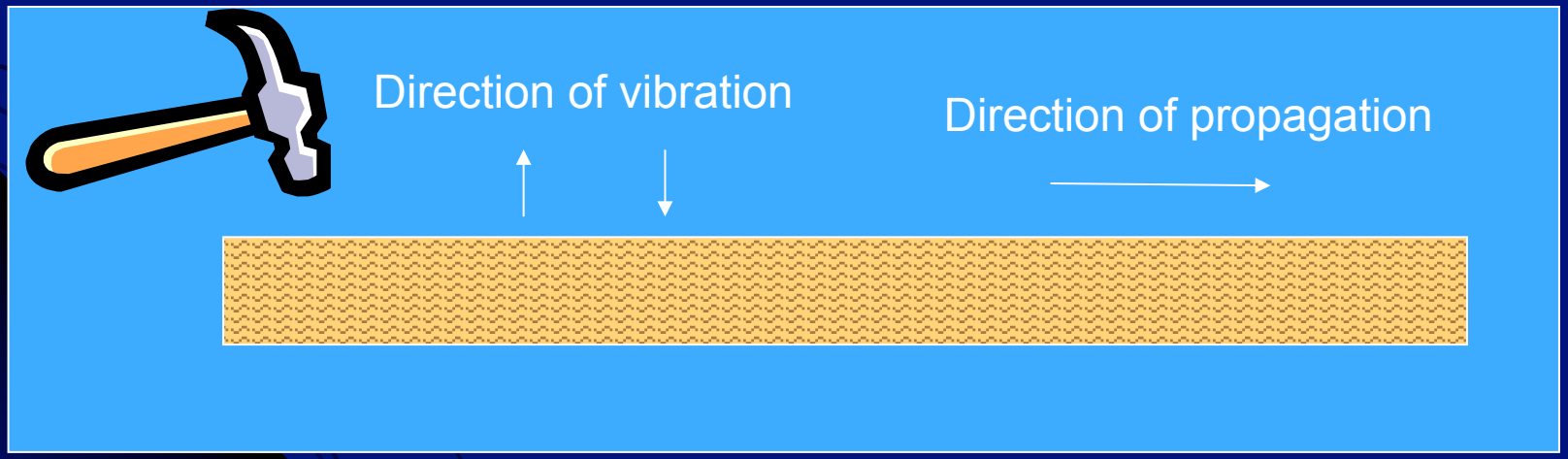
$$c = \frac{140{,}000{,}000}{11}\ \text{km/min} = 210{,}000\ \text{km/sec}$$

- This result established a uniform speed for light waves in vacuum.
- The presently accepted value is:

$$c = 299{,}792\ \text{km/sec}$$

The Aether as an Elastic Solid

- 1817 Thomas Young believed light to be waves because it had a characteristic speed. He suggested that light consists of transverse vibrations such as occur in an elastic solid.

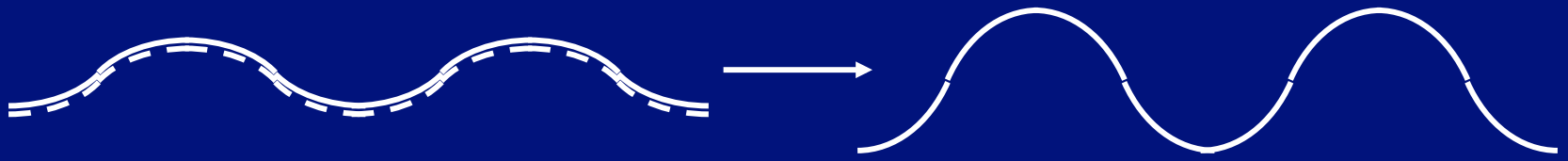


The Aether as an Elastic Solid

- Young's ideas were used successfully by scientists such as Augustin Fresnel, James MacCullagh, and Joseph Boussinesq to explain the properties of light.

Light Waves

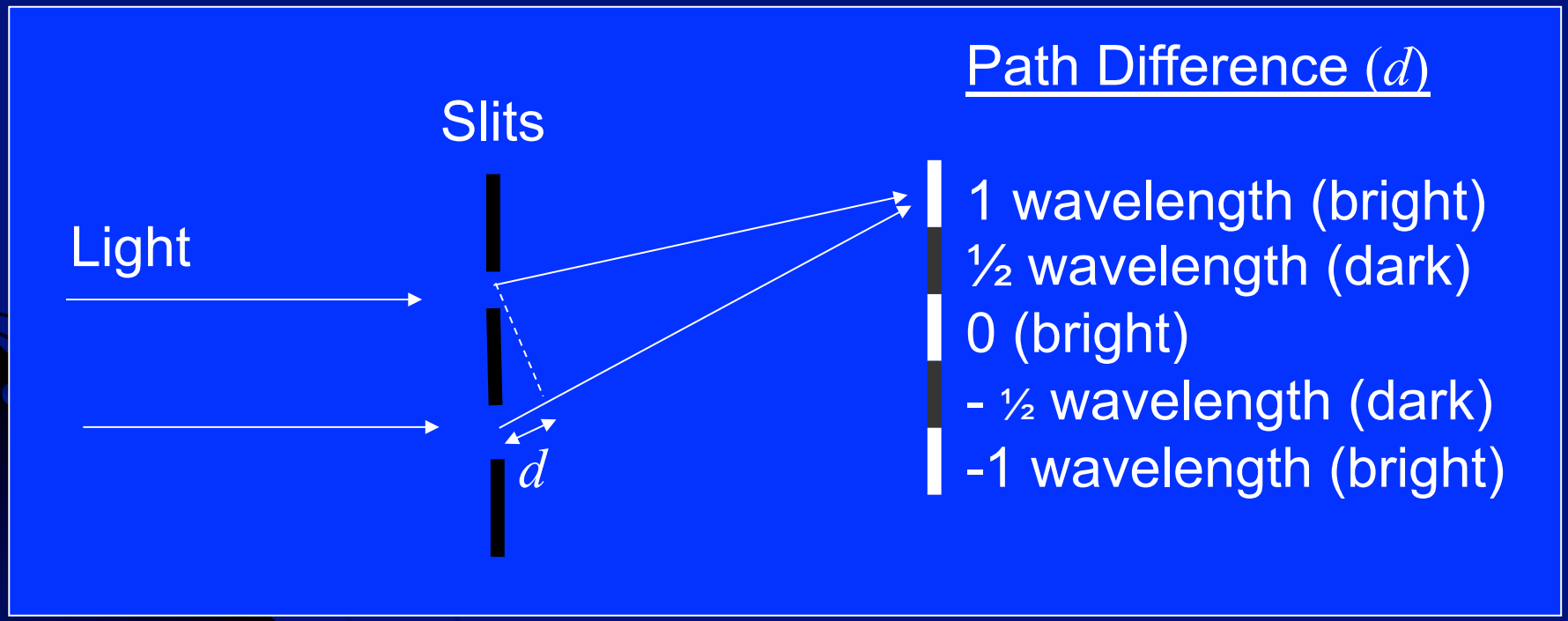
- Waves combine with interference:
- ‘In-phase’ waves add (——— + -------)



- ‘Out-of-phase’ waves cancel

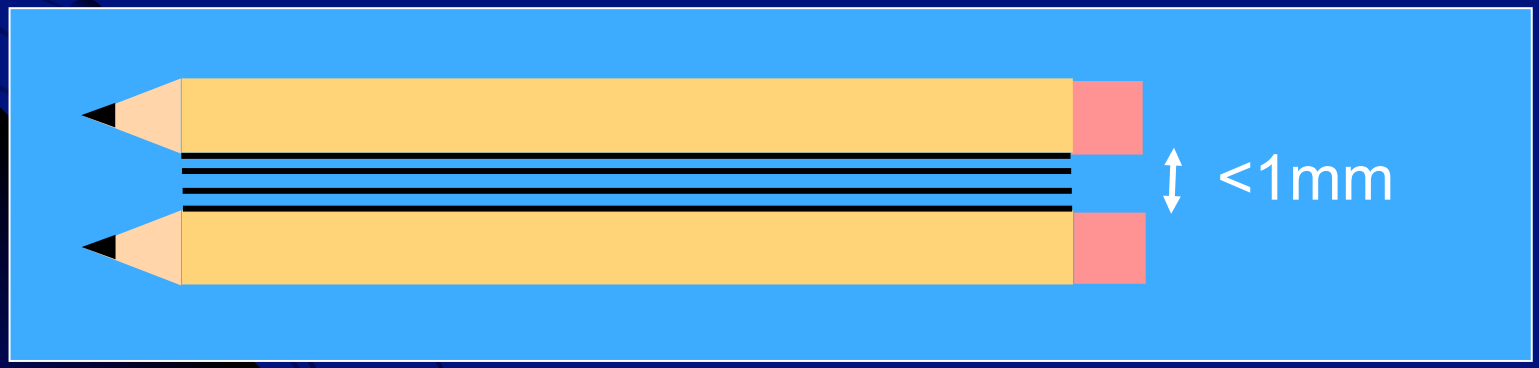
Light Waves

Gradual variation of propagation time results in interference fringes.



Diffraction

- The two-slit interference pattern persists even if there is no division between the two slits (two halves of one slit).
- You can observe this ‘diffraction’ pattern in a small slit between two pencils.



Aether Drift

- If the aether were solid, then how did Earth and planets move through it?
- Scientists supposed that the aether behaved as a solid for light but as a rarified fluid for Earth (compare with putty or wax which can bounce like a solid ball or be squeezed through a hole like a liquid).
- As Earth moved through this ‘fluid’, the speed of light should depend on its direction.

Aether Drift Experiments

- 1881-1887 Albert Michelson and E. W. Morley performed experiments which seemed to indicate a lack of relative motion between the earth and the aether. Looking at interference fringes between light propagating East-West and North-South, they measured zero difference in light speed parallel and perpendicular to the earth's motion. Therefore the aether is not a fluid.

The Theory of Relativity

- 1903 Hendrik Lorentz determined that inability to detect drift through the aether requires the difference between the squared distance and the squared propagation time between two events to be independent of observer motion, i.e.

$$x^2+y^2+z^2-c^2t^2 = \text{constant}$$

The Theory of Relativity

If the constant is zero, then:

$$x^2+y^2+z^2=c^2t^2$$

- Notice that this equation simply means:

  (Distance) = $c\times$(Propagation Time)

- This means that distance and light propagation time cannot be measured independently! It is as if all matter consisted of light waves.

Distance and Time

- The interdependence of distance and time measurements is explicit today. The meter is *defined* as the length of the path traveled by light in vacuum during a time interval $1/c$ =1/299,792,458 of a second.

The Theory of Relativity

- 1904 Henri Poincare gave the name ‘Principle of Relativity’ to the doctrine that absolute motion is undetectable. He also deduced from this principle that no velocity can exceed the speed of light.
- 1905 Albert Einstein reformulated relativity theory with the more positive assertion that the speed of light is a universal constant independent of observer motion.

The Theory of Relativity

- A key result of Einstein's analysis is the relationship between mass (m), energy (E), and the light speed (c):

$$E = mc^2$$

- This equation is not as simple as it seems because Einstein made up a new definition of moving mass. In terms of the ordinary 'rest mass' m_0:

$$m = \gamma\, m_0$$

(γ is the Greek letter gamma)

The Theory of Relativity

- The factor γ is a relationship between particle velocity and the speed of light.

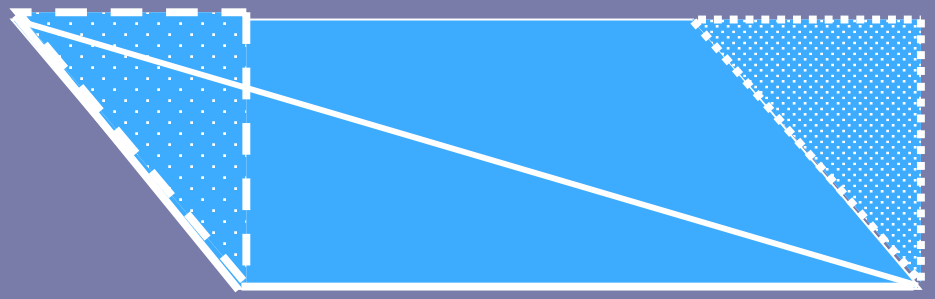
$$\gamma = \frac{1}{\sqrt{1 - v^2 / c^2}} = \frac{c}{\sqrt{c^2 - v^2}}$$

- To understand the meaning of this factor, consider the geometry of triangles…

Triangles

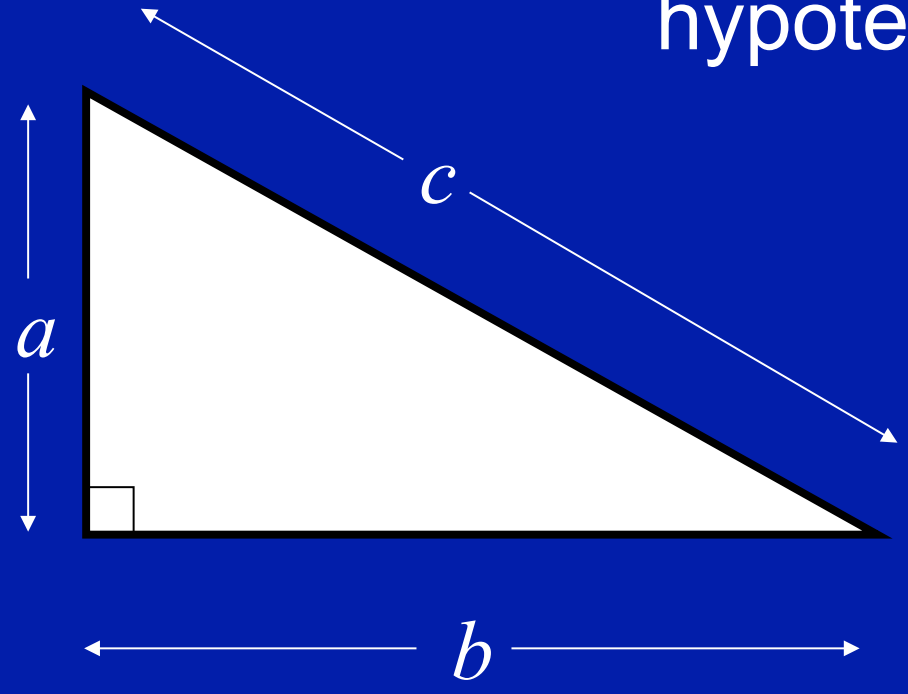
$$\text{Triangle Area} = \frac{1}{2}(\text{Parallelogram Area}) = \frac{1}{2}(\text{Rectangle Area})$$
$$= \frac{1}{2}(\text{Base} \times \text{Height})$$

(Cut and Paste to make rectangle)



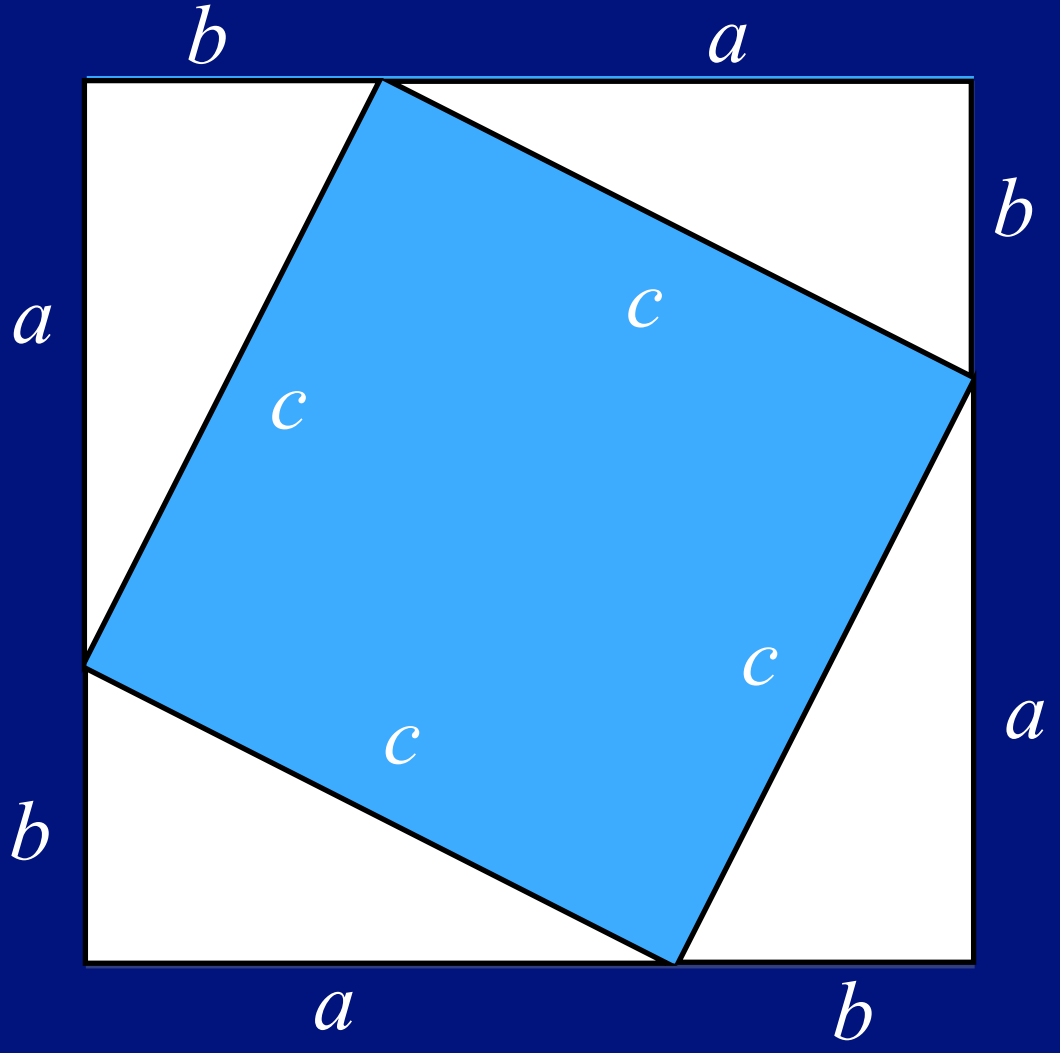
The Pythagorean Theorem

Start with a right triangle with short sides *a* and *b* and hypotenuse *c*.



The Pythagorean Theorem

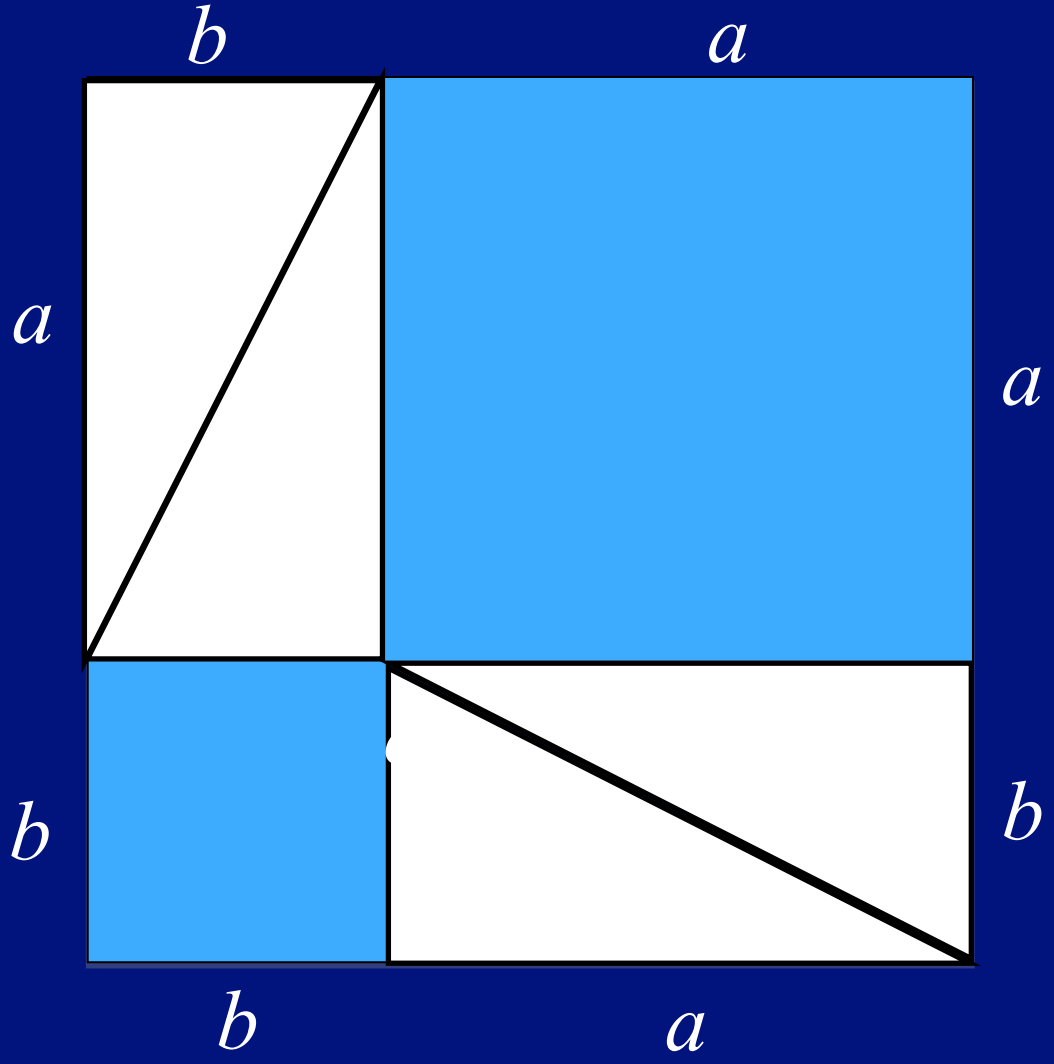
Insert four such triangles into a square with side length ($a+b$). The area of the outlined blue square is c^2.



The Pythagorean Theorem

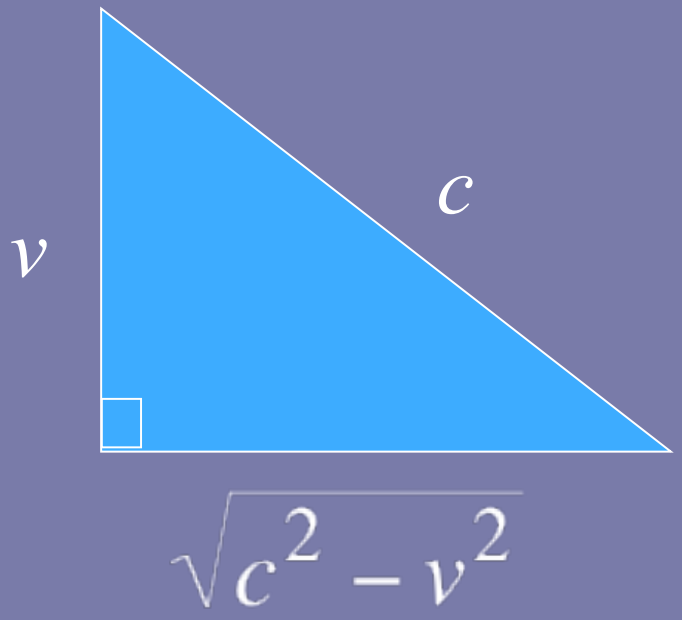
Rearrange the triangles. The area of the blue region is now clearly a^2+b^2.

Therefore: $a^2+b^2=c^2$



The Gamma (γ) Factor

According to the Pythagorean Theorem, γ is the ratio between the hypotenuse of a right triangle and one of its sides. This is the velocity triangle:



$$\gamma = \frac{c}{\sqrt{c^2 - v^2}}$$

Interpretation of Mass

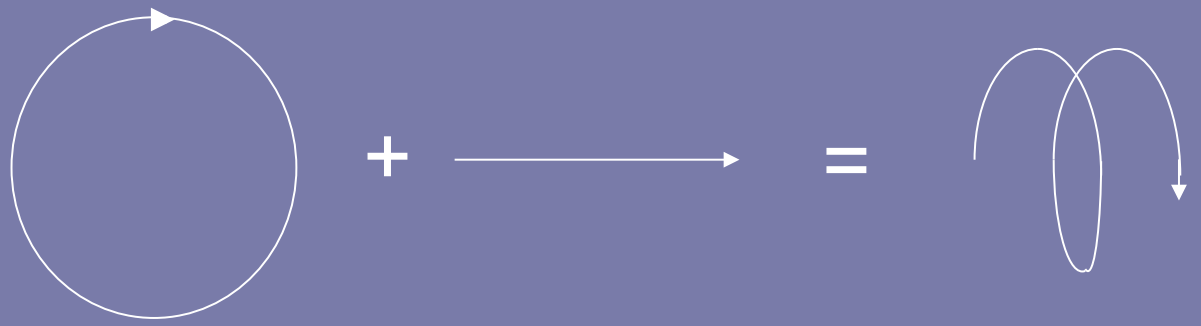
Suppose that matter propagation has two components:

1. Circular motion (oscillating motion is also possible)
2. Linear motion

If the circular motion is in a plane perpendicular to the linear motion then the path is a helix (spiral).

If one component of the circular motion is aligned with the linear motion then the path is called a cycloid. The circular and linear components still satisfy the Pythagorean relation.

Helical & Cycloidal Motion



$d_C = 2\pi r$ $\quad$ $d_T = vt$ $\quad$ $D = ct$

$$D = ct = \sqrt{(2\pi r)^2 + (vt)^2} = 2\pi r \sqrt{\frac{(2\pi r)^2 + (vt)^2}{(2\pi r)^2}}$$

$$= 2\pi r \sqrt{\frac{(ct)^2}{(ct)^2 - (vt)^2}} = \gamma 2\pi r$$

Velocity Triangle

Relate total speed c and circulation speed v_C:

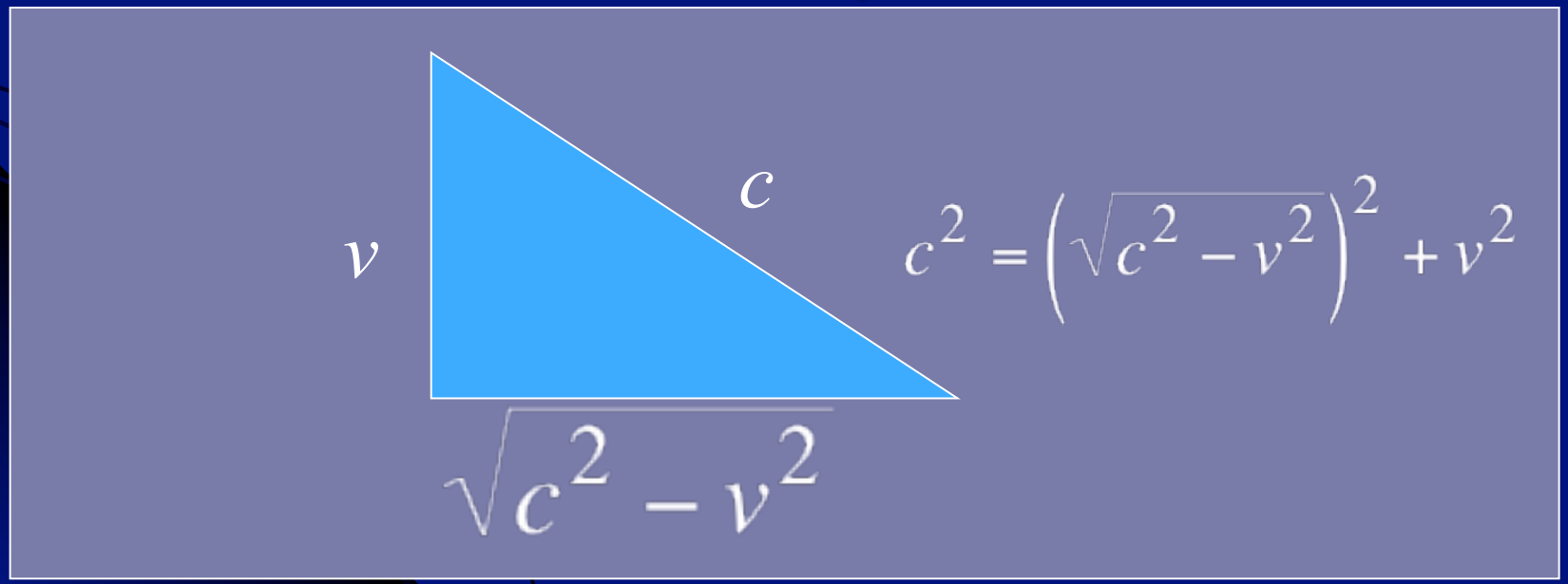
$$c = v_C \sqrt{\frac{c^2}{v_C^2}} = v_C \sqrt{\frac{c^2}{c^2 - v_T^2}} = \gamma v_C$$

γ is the ratio between the total wave speed and the circulation speed.

Energy Triangle

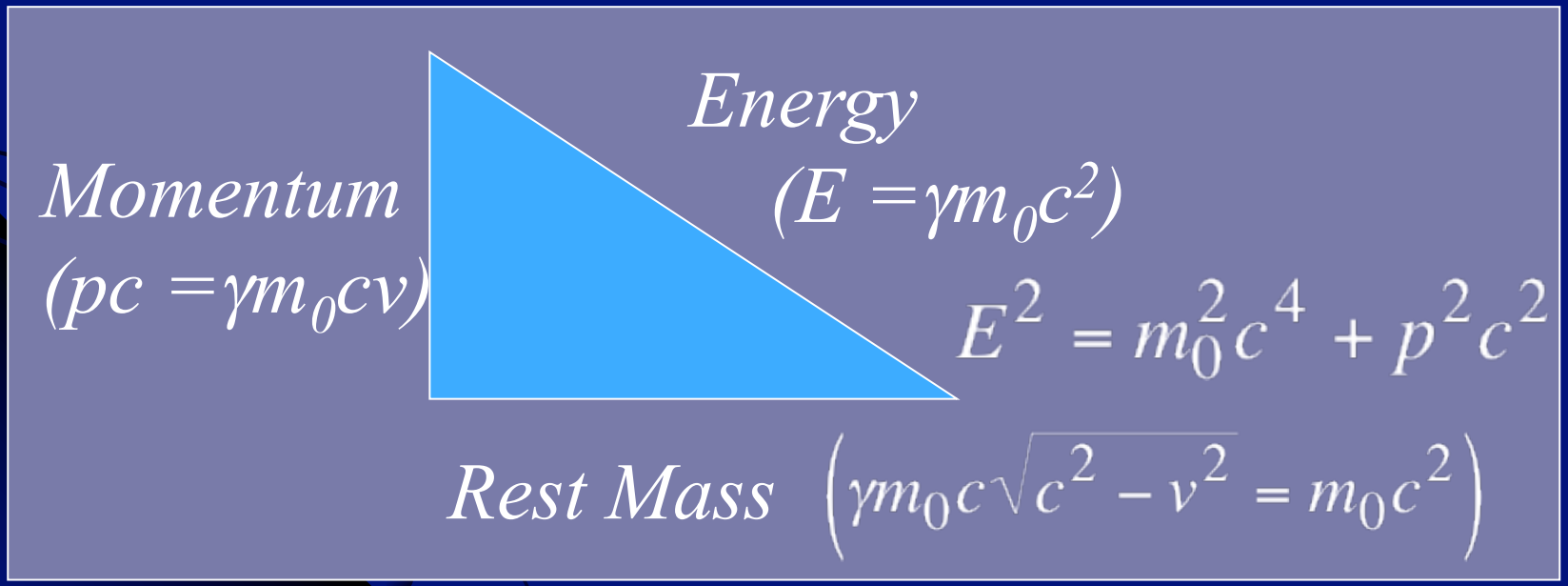
Consider the right triangle representing a spiral wave: the three sides are average velocity, circulating velocity, and the speed of light.

Multiply each side by $\gamma m_0 c$.



Energy Triangle

Energy is proportional to the speed of light.
Momentum is proportional to average velocity.
Rest Mass is proportional to circulating velocity.



Energy Equation

We can therefore write this equation for energy:

$$E^2 = \left(mc^2\right)^2$$

$$= \left(\gamma m_0 c^2\right)^2$$

$$= m_0^2 c^4 + p^2 c^2$$

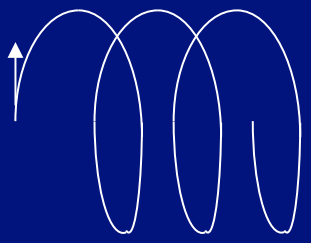
This is another form of Einstein's equation.

Twin Paradox

- Relativity theory predicts that if one twin stays put while the other goes on a high-speed voyage, the traveling twin will be younger (ages less) than the stationary twin.

Twin Paradox

- A clock counts the number of circular orbits executed by a circulating matter wave.
- A matter wave with translational motion travels farther (at the same speed of light) than a stationary matter wave during each rotation cycle. Therefore a moving clock ticks slower than a stationary one, and a moving twin ages slower than a stationary one.



Twin Paradox

- The twin paradox is not just hypothetical.
- Unstable particles moving nearly the speed of light have significantly longer lifetimes than otherwise identical particles with slower motion.
- GPS navigational systems must adjust clocks for relative motion.

One More Question

Why does matter appear to propagate at the speed of light?

Matter as Waves

- 1900 Max Planck explained the distribution of thermal radiation by supposing light to be emitted by vibrators whose energy (E) can only have integer multiples (n) of the vibration frequency (f) multiplied by a universal constant (h).

$$E = nhf$$

Such a restriction is called ‘quantization’.

Photo-Electric Effect

- 1905 Einstein used quantization of radiation to explain the photo-electric effect, in which the frequency of light (rather than the brightness) must exceed a certain threshold in order to liberate electrons from a metal.

Quantization

- 1913 Niels Bohr used quantization of angular momentum and energy to derive energy levels and spectral frequencies of the hydrogen atom.

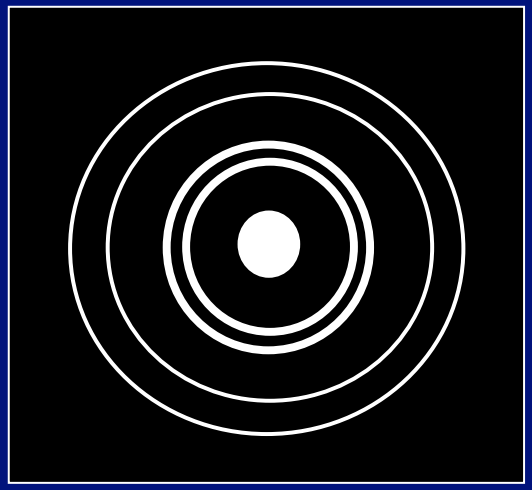
Electron Waves

- 1924 Louis Victor de Broglie proposed in his doctoral thesis that electrons have a wave-like character with the same relation between momentum and frequency as for light waves.

Electron Waves

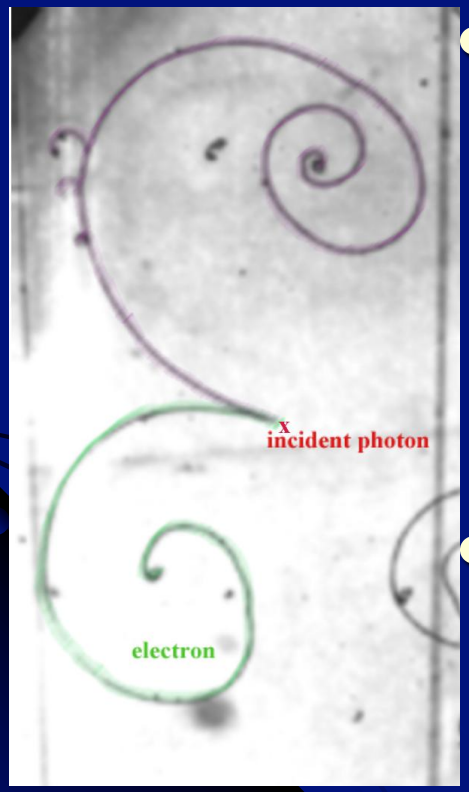
- 1927 Clinton Davisson and Lester Germer (and independently George Thomson and Alexander Reid) confirmed the wave nature of electrons by demonstrating diffraction of electrons by crystals.

Matter as Waves



Electron scattering from crystals yields a diffraction pattern characteristic of waves. A similar diffraction pattern can be obtained using x-rays of the same wavelength.

ELECTROMAGNETISM
1933



- Patrick Blackett discovers opposing spiral tracks in a magnetized cloud chamber, indicating positron/electron pair production from cosmic gamma rays. This conversion of electromagnetic wave energy to matter confirms de Broglie's wave hypothesis.
- Matter, like light, evidently consists of "affections" of the aether as envisioned by Maxwell.

http://teachers.web.cern.ch/teachers/archiv/HST2002/Bubblech/mbitu/ELECTRON-POSITRON2-piece.jpg

Matter as Waves

- Experiments indicate that matter consists of waves!

Matter as Waves

- de Broglie used the wave model of electrons to derive Bohr's angular momentum and energy levels of the Hydrogen atom.

$$(\text{mass}) \times (\text{circular acceleration}) = \frac{m_e v^2}{r}$$

$$= F = k_e \frac{e^2}{r^2} = (\text{electrical force})$$

$$(\text{multiple of wavelength}) = n\lambda = 2\pi r = \text{Circumference}$$

$$(\text{particle momentum}) = m_e v = p = \hbar k = \frac{h}{\lambda} = (\text{wave momentum})$$

Matter as Waves

- de Broglie used the wave model of electrons to derive Bohr's angular momentum and energy levels of the Hydrogen atom.

$$n\lambda = 2\pi r$$

$$p = m_e v = \hbar k = h/\lambda$$

$$L = rp = rm_e v = \frac{hr}{\lambda} = \frac{hr}{2\pi r/n} = \frac{nh}{2\pi} = n\hbar$$

$$E_n = -\left(\frac{\left(k_e e^2\right)^2 m_e}{2\hbar^2}\right)\frac{1}{n^2} = -\frac{R_E}{n^2}$$

Matter as Waves

- It just so happens that the frequencies of light in the hydrogen spectrum satisfy the relation:

$$hf = R_E\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)$$

- Assuming that energy of a light wave is proportional to frequency yields the difference between two of de Broglie's orbit energies:

$$\Delta E = hf = R_E\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)$$

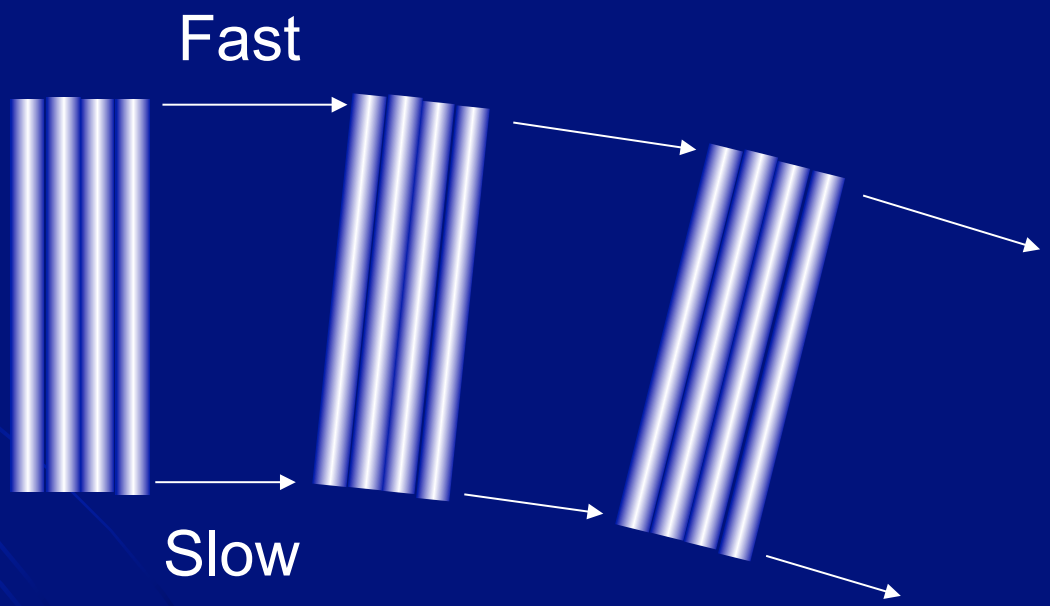
Gravity

Gravity is a reduction of wave speed in the vicinity of massive objects (a prediction of General Relativity).

For example, compression of a solid aether would reduce the wave speed.

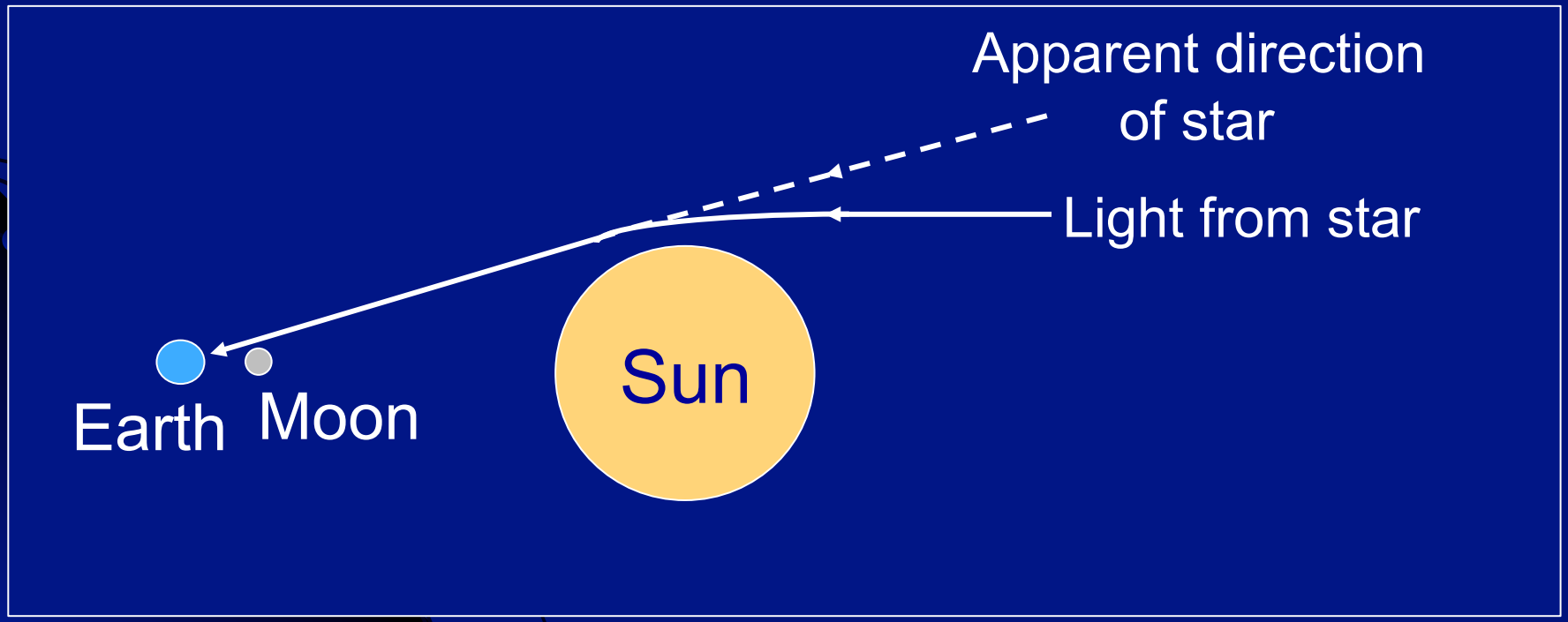
Gravity

Waves refract (bend) toward regions of slower wave speed.



Gravity

- During a solar eclipse, the positions of stars near the direction of the sun are observed to be shifted. This confirms that the light rays from those stars are bent as they pass near the sun.



Summary

- Matter consists of wave packets which propagate along curved paths at the speed of light.
- Mass represents circular or oscillating motion.
- Momentum represents linear motion.
- Energy represents total motion.
- Gravity represents wave refraction.

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