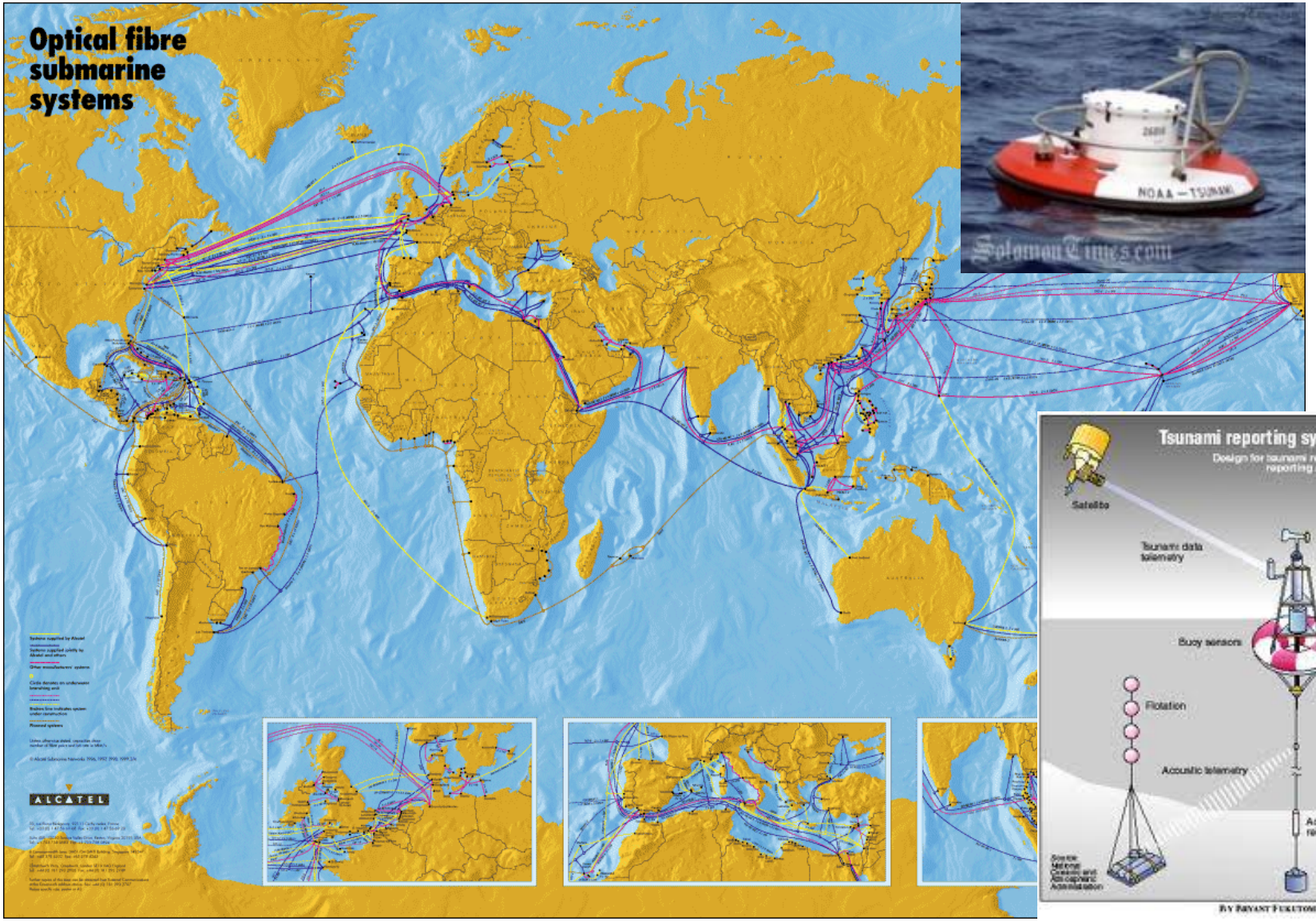

"The Great Wave" Hokusai B-1760

# Communicating by Waves



# Flow of Talk

-Waves are all around us – both mechanical and EM waves

-Huge differences in scale [sea waves to X-rays] but all obey the same laws [refraction, diffraction, reflection etc]

-Wave refraction (bending) leads to guided mechanical and EM waves

-Wave diffraction (behaviour of waves when they encounter obstacles) important for our understanding of light and structure of materials.

-As wavelength decreases we move into regions where wave/particle duality becomes more evident.

-At the atomic level, fundamental particles (eg electrons) can be viewed as waves

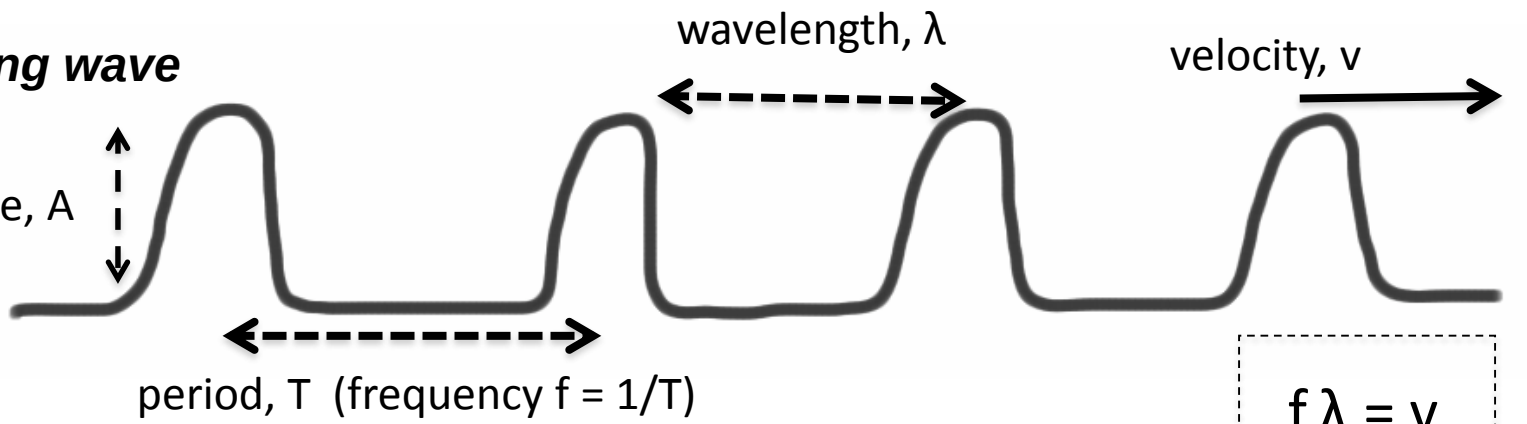
-At a sub-atomic level string theory considers all fundamental particles to comprise microscopic vibrating strings; this theory will be supported by discovery of the Higgs Boson.

# What is a Wave ?

A travelling wave is a disturbance that moves through a medium, eg sound wave through water or air, surface wave on the sea, electromagnetic wave ( through a vacuum). Creation of a wave needs energy input and a restoring force.

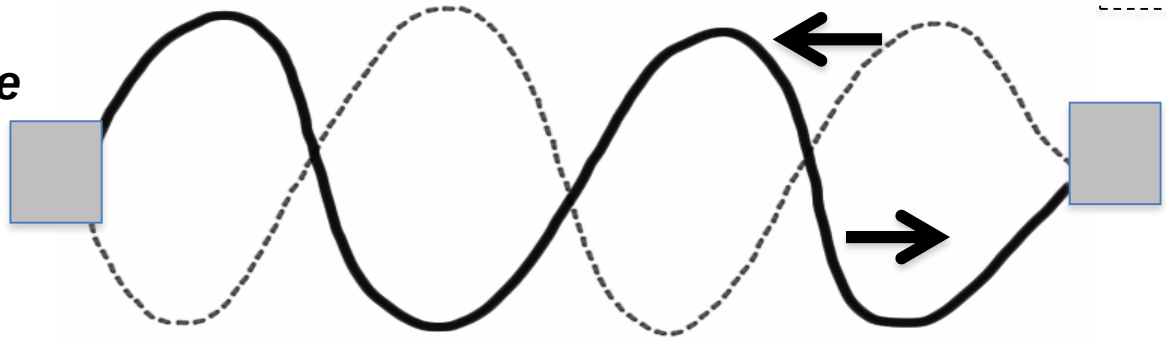
## Some definitions

***Travelling wave***




$f.\lambda = v$

***Standing wave***



# Key Points

- **A wave is a disturbance** that moves through a medium.
  -on a string, through water, sound (air), electromagnetic wave ( a vacuum)

- **A wave transports energy**, but there is no transport of matter
  eg sea wave (message bottle, lump of wood)

- **All waves undergo, refraction, diffraction, reflection, interference**

- **Characterized by amplitude, frequency/wavelength, velocity**, **phase**

**Waves can be:**

***Transverse***: displacement of medium perpendicular to direction of propagation
string, sea, em, Mexican !

***Longitudinal***: displacement of medium is in direction of travel [eg sound wave]

# Waves are Everywhere

## *Mechanical waves*

**Sound wave, vibration of a string**



**Breaking sea waves**

surging, spilling, (plunging)

**Gravity cloud waves** (George Biddell Airy 19th Century)
Interface between two media, restoring force gravity or buoyancy)

# Exotic Mechanical Waves

Somewhere nice


Severn tidal bore
(nr Bristol !)

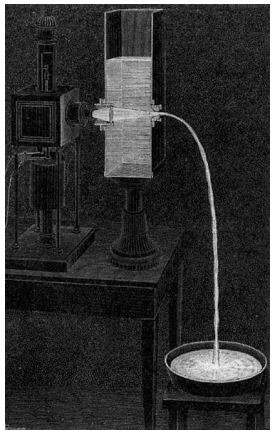
A wavefront
followed by a train of
solitons

Morning Glory cloud
formation in QLD,
Australia

60 km/hr; 200 m above
ground;>100km long

Soliton waves (John Scott Russell 1834) “that singular and beautiful phenomenon”
A wave that has a single crest and moves without changing speed or shape

# Electromagnetic (EM) waves



"The Light Fountain" 1884

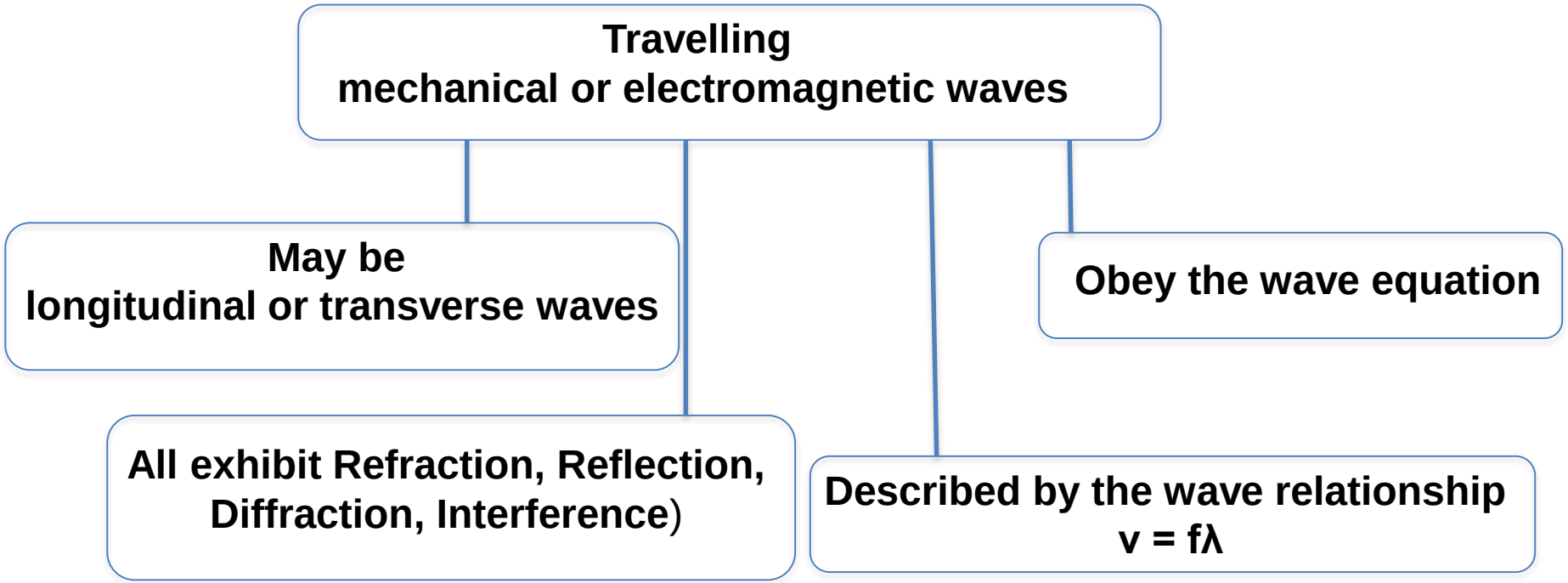

Soliton waves across the Nullabor plane 2000 [3000 km]

Radio waves

X Rays

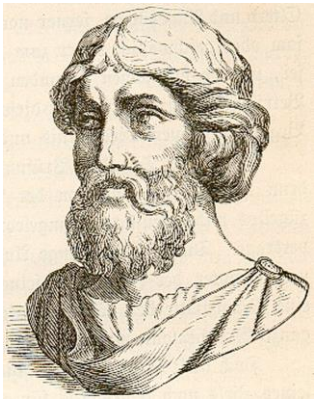
Properties of fundamental particles (eg electrons, quarks) described in terms of string vibrations (string theory)

# Wave Characteristics




http://hyperphysics.phy-astr.gsu.edu/hbase/sound/trawvcon.html#c1

# Mechanical Waves



Pythagoras
570 - c. 495 BCE.

*Most of the understanding of waves grew from thoughts and ideas about sound and music.*

-realised the pitch of a musical note depends upon the length of the string. Thus correlated the intervals of the musical scale with simple numerical ratios.

-convinced that God made the universe according to a mathematical plan.

-proposed that planets were separated by intervals corresponding to the harmonic lengths of strings and

-their movements gives rise to a musical sound called the "harmony of the spheres." [music of instruments; music of the body; music of the spheres]

-Plato (450 BCE) also upheld this theory.

-Kepler (1570) started off with this belief (2000 years later)

http://en.wikipedia.org/wiki/Pythagoras

# Wave Equation

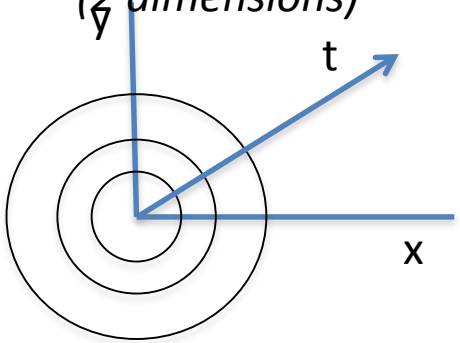
1564-1642

*? linked the pitch of the sound to frequency*

1627 –1691

*? proved that sound cannot travel through a vacuum.*

*A noise impulse or pebble in pond (2 dimensions)*



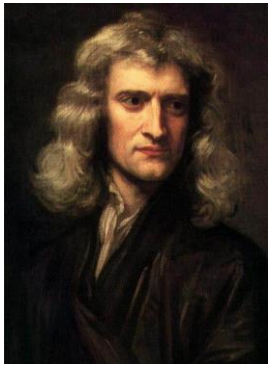

*? first mathematical description of how sound travels, published in ?*

1717-1783

*? wave equation*

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \frac{1}{v^2}\frac{\partial^2 u}{\partial t^2}$$

*2nd Order Partial Differential Equation*



1642 –1727

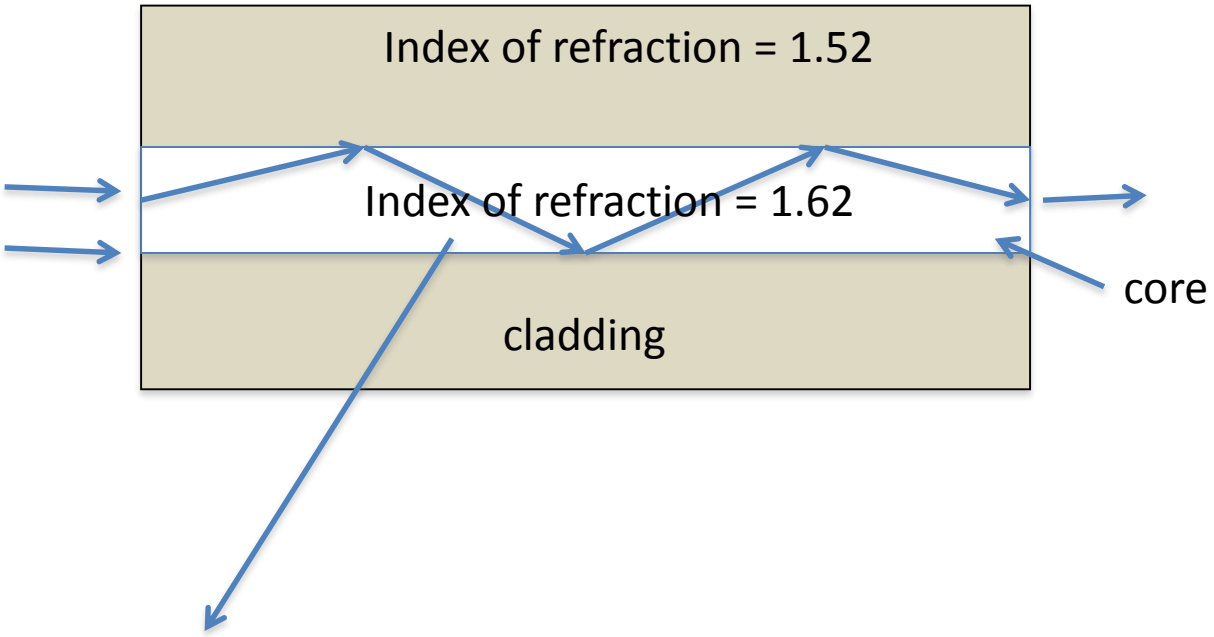
- Equation includes wave velocity v, which can change giving rise to refractive effects

# Refraction and Guided Waves

-Refraction easiest to demonstrate using an optical wave, but applicable to all other waves.

-Refraction (bending) occurs when a wave passes from one medium to another with a different refractive index, ie a difference in speed of transmission

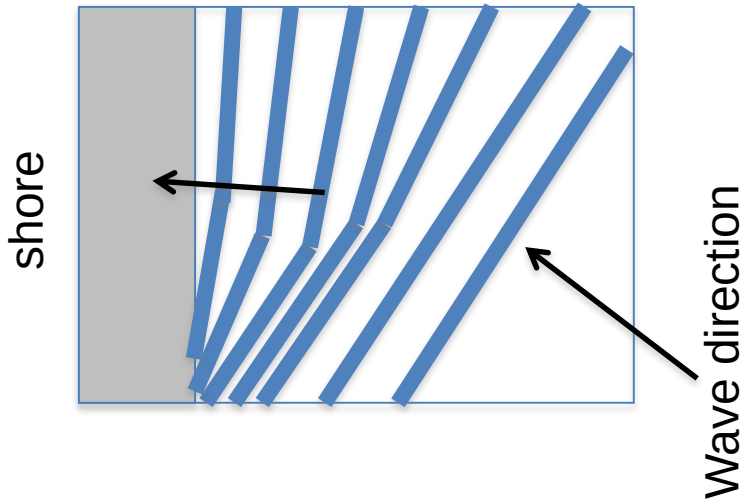
-The wave stays within the layer with the highest refractive index ie the SLOWEST speed




Speed of light = $3.\ 10^{8}$ / 1.62 $m.s^{-1}$

# Sea Surface Waves & Refraction

- Formation of wind waves, surface tension and gravity
- Wave energy μ to square of wave height and fourth power of wind speed
  1 metre waves dissipate 10kW per metre of beach




- In shallow water, waves slow down, wave length shortens, frequency stays same [v=fλ]

- Part of wavefront that enters shallow water first will begin to slow while the deep-water part keeps moving at its original higher speed, causing the wave to bend or refract.

# Refraction undersea and in the Stratosphere

Under the sea and in the stratosphere similar mechanisms occur that cause refraction and the guiding of sound waves.


Atmospheric sound channel --- +15 km

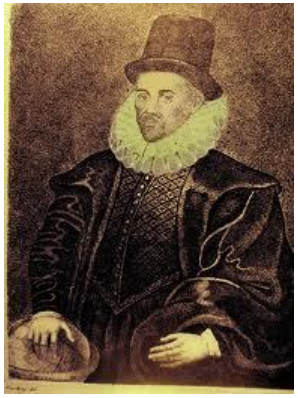
***Refraction guides sound waves***

Undersea sound channel --- -1 km

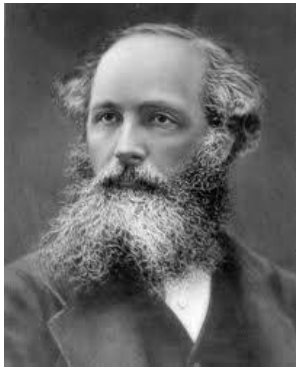
http://stratocat.com.ar/indexe.html

http://muller.lbl.gov/teaching/Physics10/old%20physics%2010/pages/Atmosphere.html

# Development of Electromagnetic Wave Understanding



- William Gilbert (Colchester:-1544-1603) :
  -electricity & magnetism separate effects
- Hans Orsted (Denmark: 1777-1851) :-
  -relationship between electricity and magnetism (compass needle)
- Michael Faraday FRS (1791-1867):
  -magnetic fields and currents



- James Clerk Maxwell FRS, FRSE (1831-1879):
  formulated equations defining em waves
- Hertz [D] [1857-1894] confirmed theory experimentally
- *Heaviside [1850-1925]: reformulated Maxwell eqns

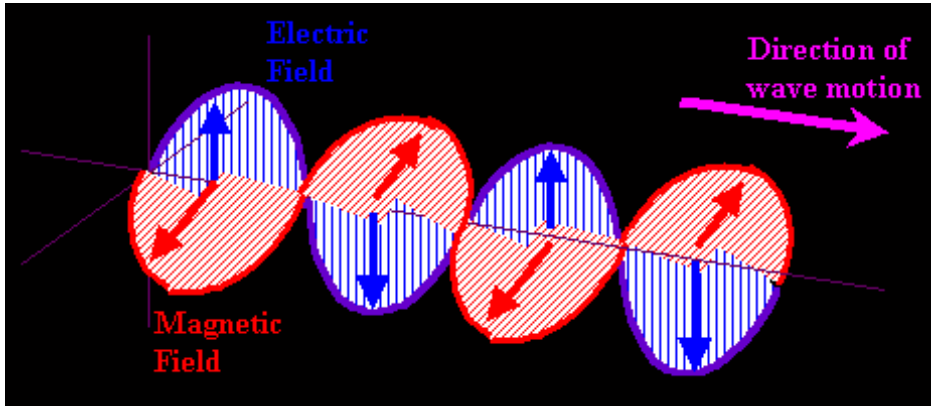
*Shall I refuse my dinner because I do not fully understand the process of digestion?

# Maxwell's (in)famous equations

$$\nabla \cdot \mathbf{D} = \rho_f$$
$$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

B is magnetic flux density related to H magnetising field
D electric flux density, related to E the electric field
J current density, ρ is charge density.

James Maxwell 1831-79; equations describe the inter relationship between magnetic and electric fields within an electromagnetic wave, it shows how a varying electric field is accompanied by a magnetic field each at right angles to the other.




Transverse Wave

*"self-propagating transverse oscillating wave of electric and magnetic fields"*

# The Photon

A changing magnetic field induces a changing electric field and vice-versa—the two are linked. These changing fields form electromagnetic waves. They differ from mechanical waves in that they do not require a medium to propagate.

The energy of an electromagnetic wave is quantized, and is emitted and absorbed as discrete packets of energy called photons, eg light is emitted in exact multiples of photons. The energy of a photon is μ to the frequency, related by the Planck–Einstein equation (1905):

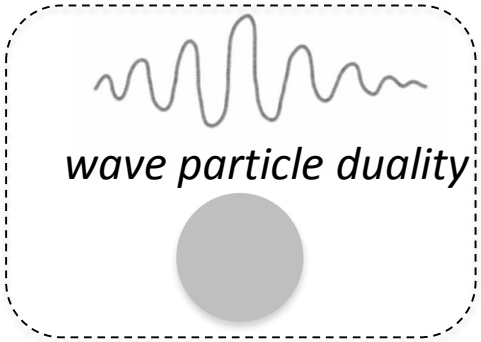
*Planck's constant*

*speed of light*

$$E = hf = \frac{hc}{l}$$

*wavelength*

"first equation of quantum mechanics"

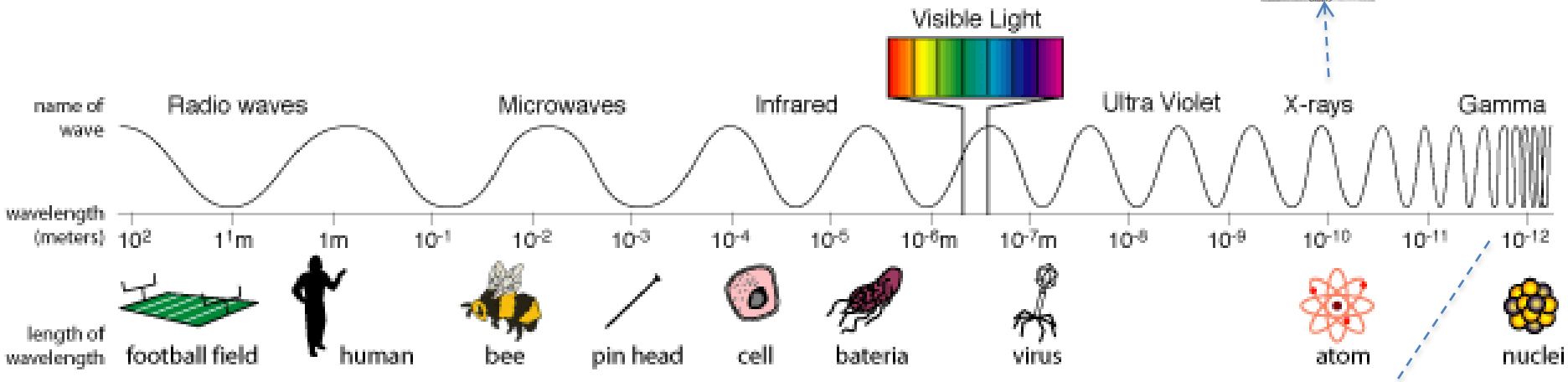



h= 6.626x10$^{-34}$ J.s = 0.000000000000000000000000000006626 J.s

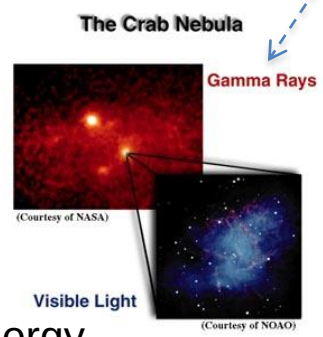
# The Electromagnetic Spectrum

*Mrs Wilhelm Roentgen's Hand (1895)*

*boundary of particles/waves*




Increasing energy, $E = \frac{hc}{l}$

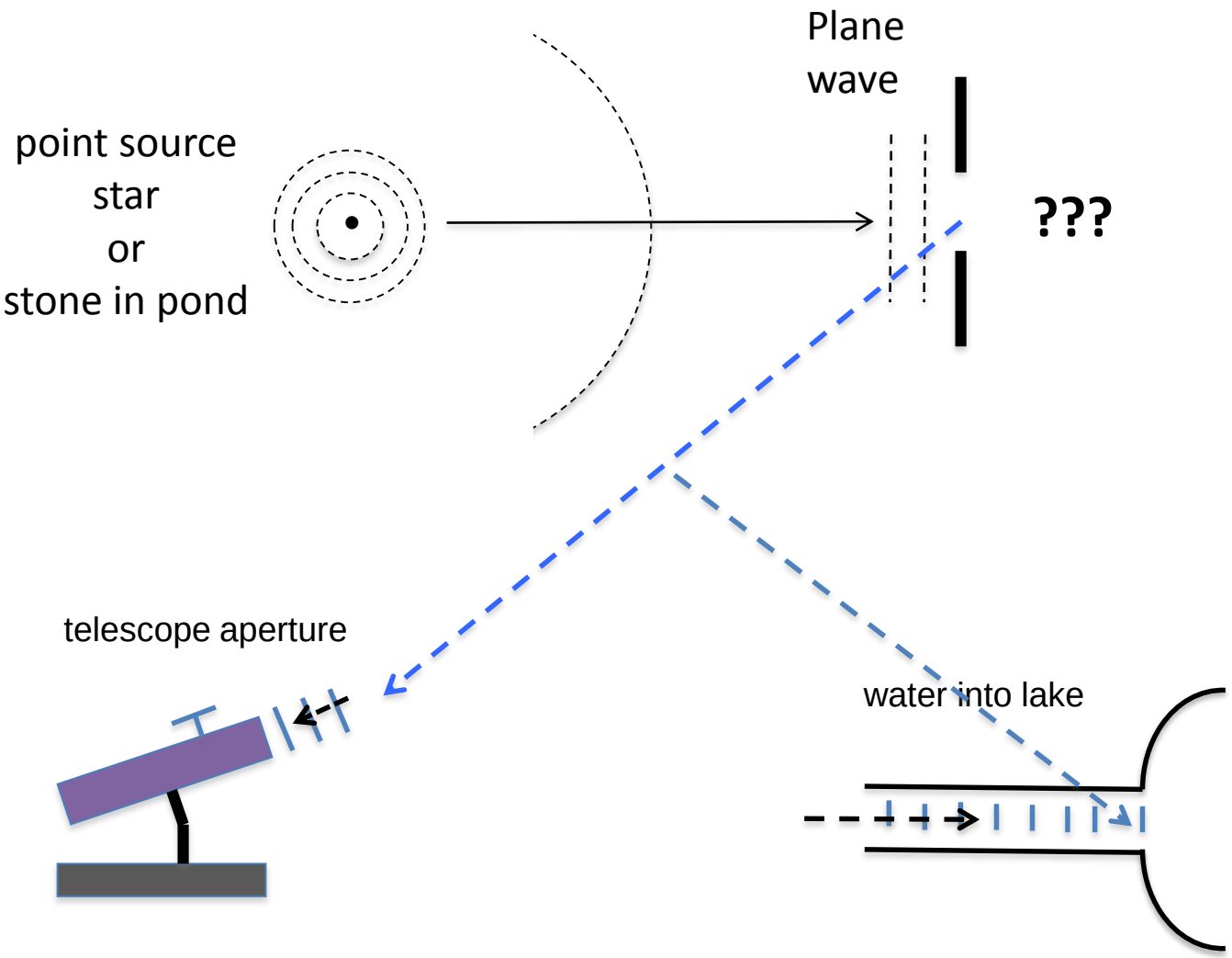



Gamma rays-shortest wavelength & most energy

http://science.hq.nasa.gov/kids/imagers/ems/waves3.html

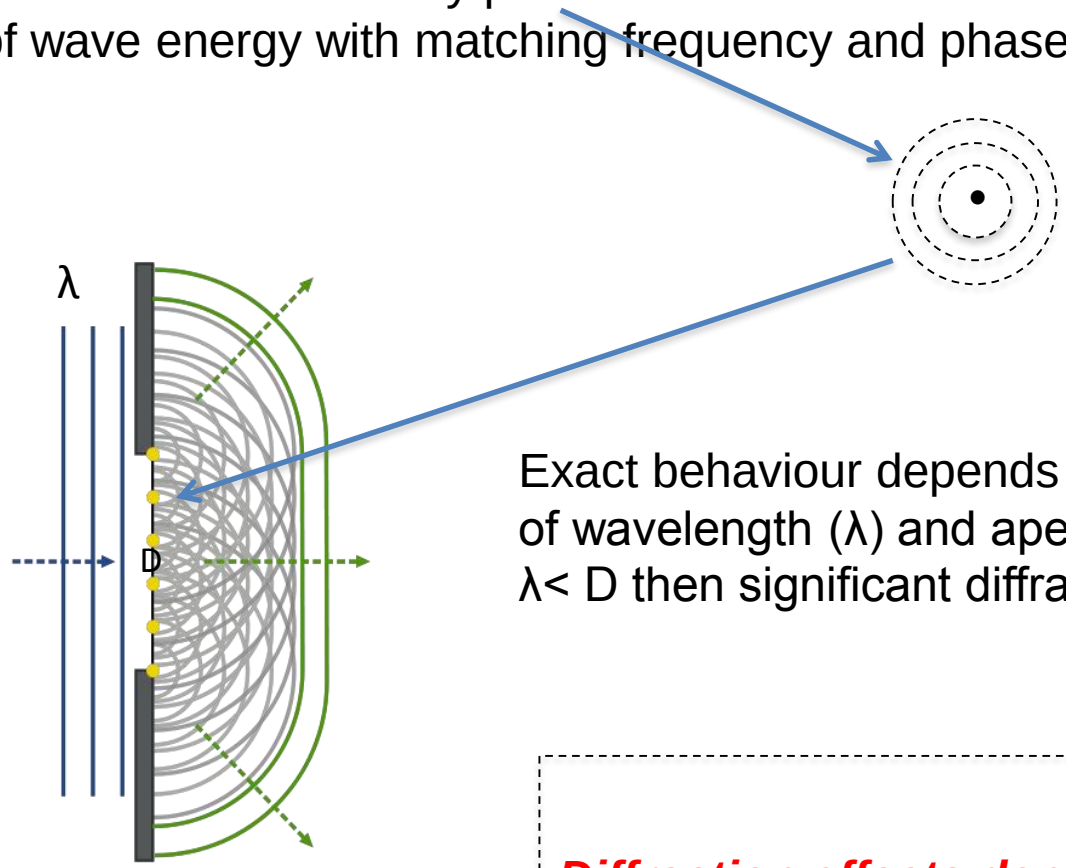
# Diffraction

*behaviour of waves when they encounter obstacles*



# (Christiaan) Huygens* Principle

He assumed that every point on a wavefront acts like a new source of wave energy with matching frequency and phase.




Exact behaviour depends on relative size of wavelength (λ) and aperture opening D. If λ< D then significant diffraction effects are observed.

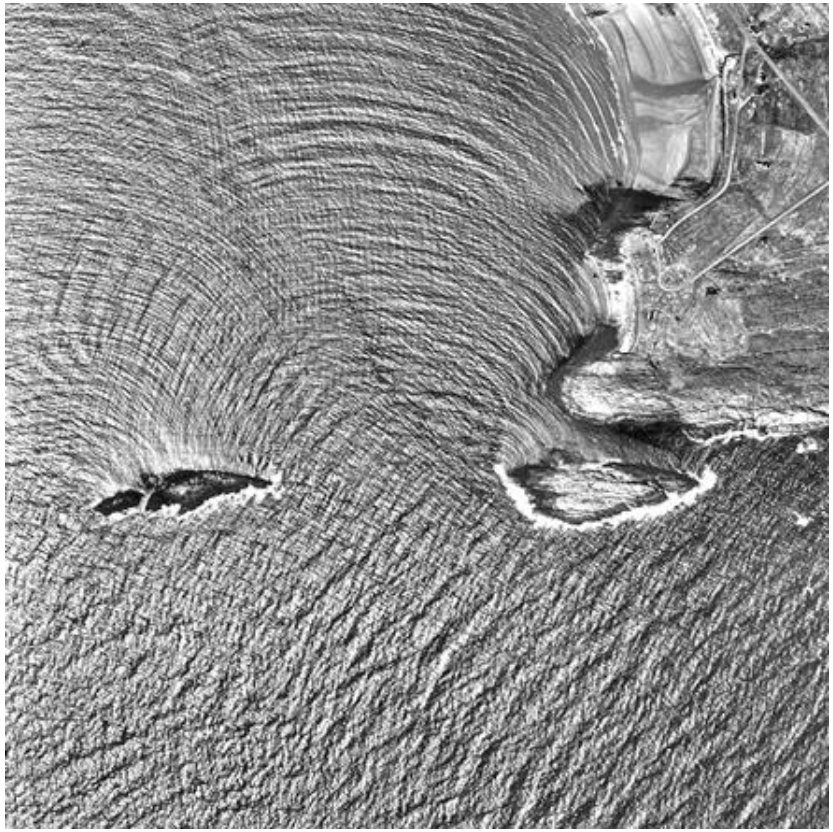
***Diffraction effects depend on*** $\frac{l}{D}$

*1629-1695: Also discovered true nature of rings of Saturn, invented first practical pendulum clock & microscope eyepiece*

# Diffraction of Sea Waves

-Diffraction occurs with all waves, including sound waves, water waves, and electromagnetic waves .
-As physical objects have wave-like properties (at the atomic level), diffraction also occurs with matter .

This photo shows water wave diffraction near the northern coast of Norway.

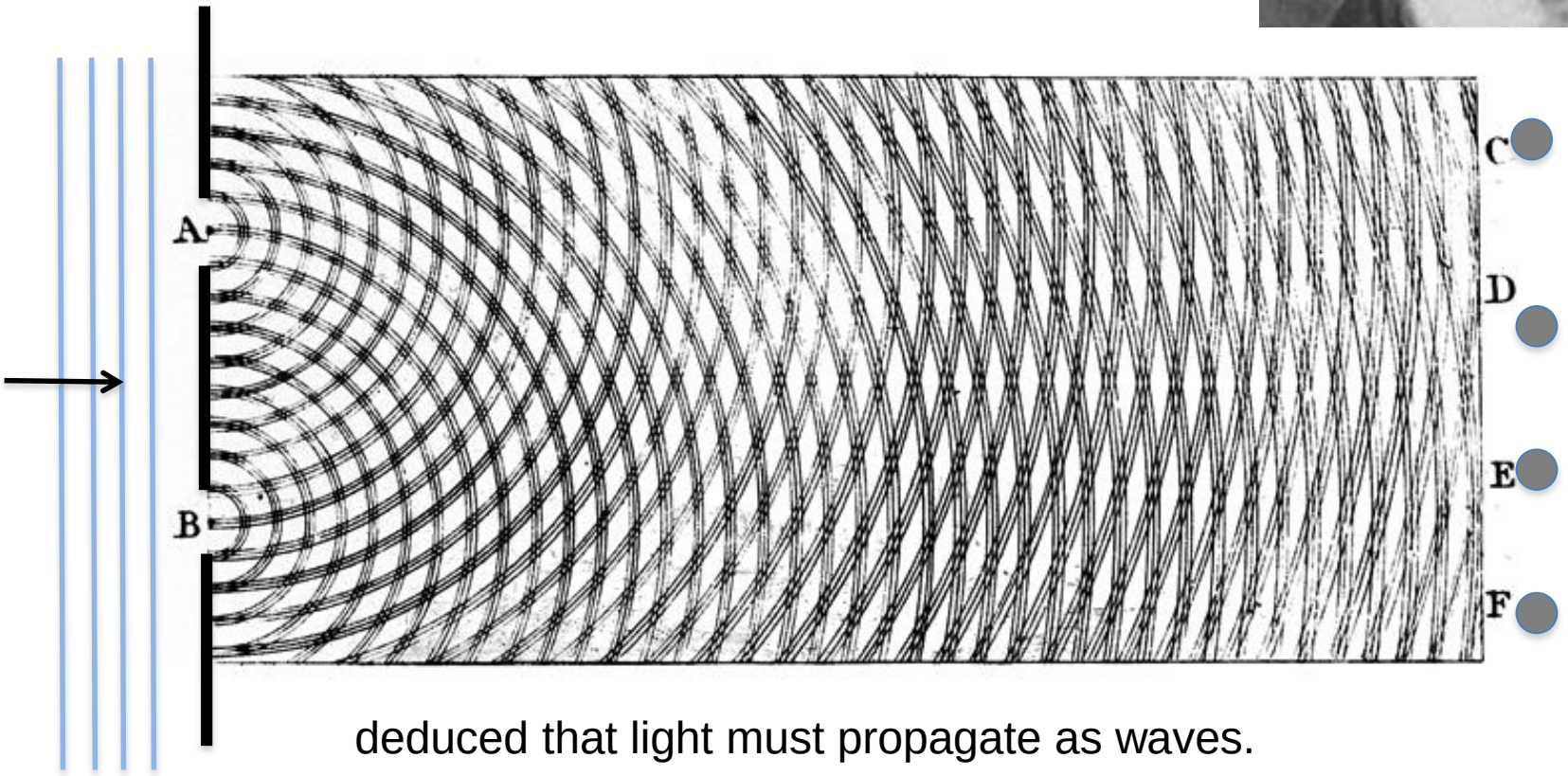


http://www.compadre.org/informal/features/featureSummary.cfm?FID=406

# Thomas Young Dual Slit Experiment 1803

## -diffraction of light waves-

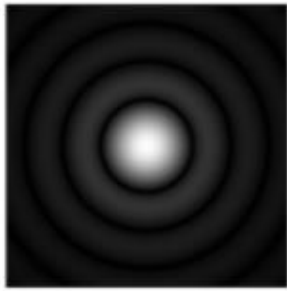
Young's sketch of experiment at Royal Society 1803



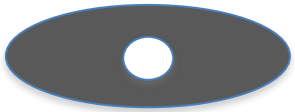

deduced that light must propagate as waves.

http://en.wikipedia.org/wiki/Diffraction

# Demo



*Airy disk*

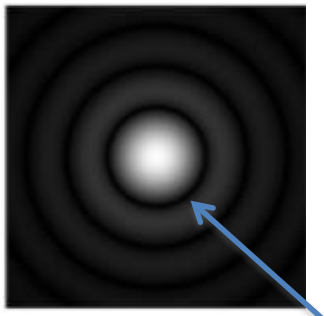


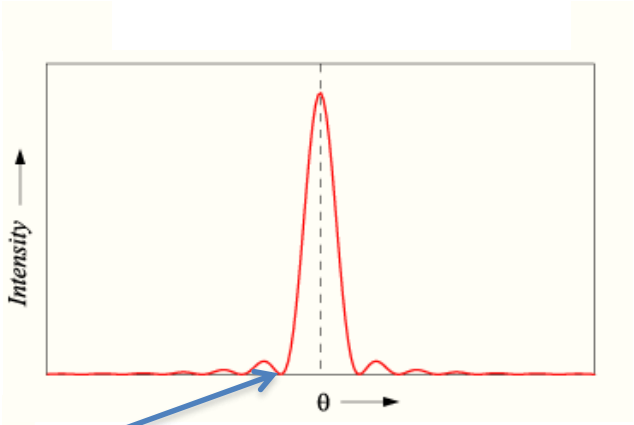
200 µm

# Limits to Resolution

Diffraction matters in telescopes as it limits resolution, ie ability to separate objects.

*Airy disk*





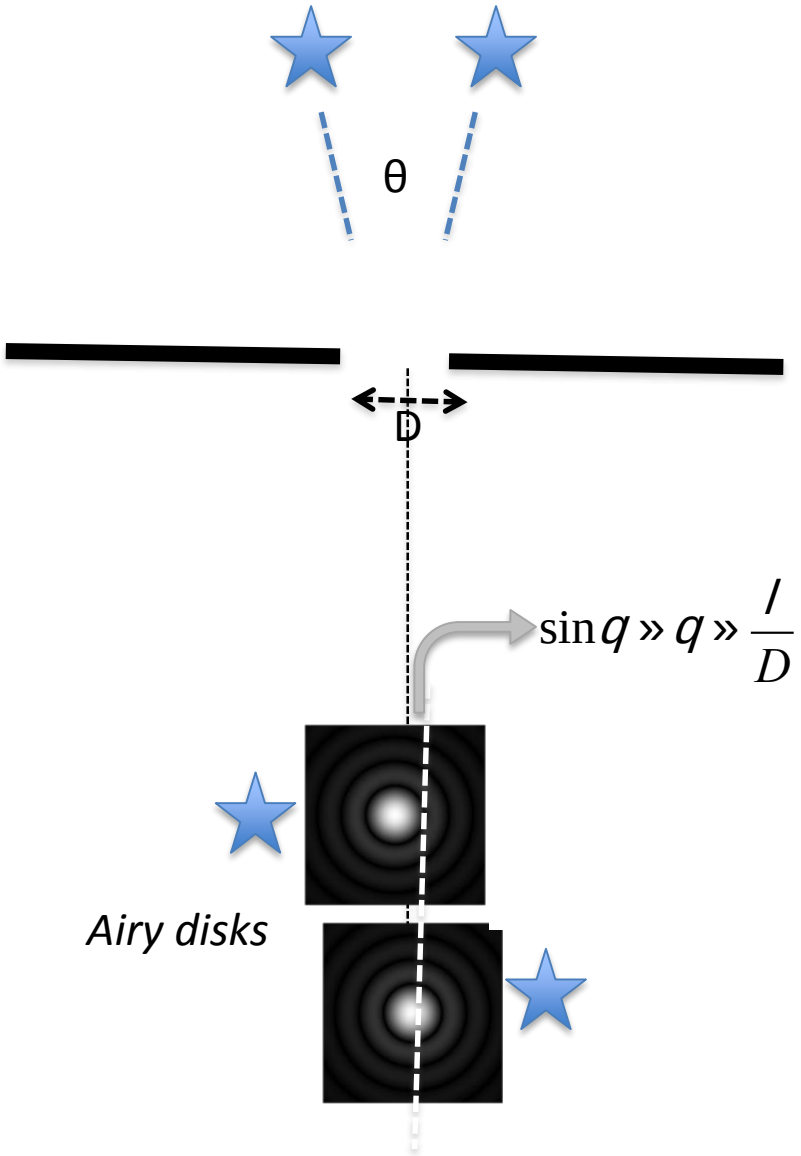

$$\sin q \approx q = \frac{l}{D}$$

First explained in “On the Diffraction of an Object-Glass with Circular Aperture” by George Biddel Airy (1835)

-Born 27 July 1801
-Colchester Royal Grammar School
-Astronomer Royal
-Son responsible for instrumentation specs in observatory


SIR GEORGE BIDDELL AIRY.

# Diffraction through a Telescope




For Tomlin

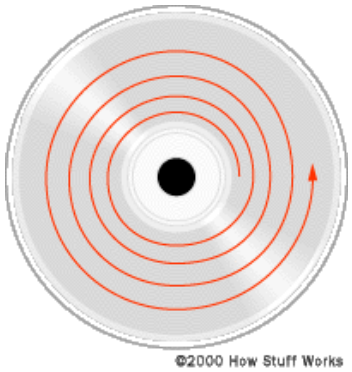
$$\sin q \approx q = \frac{l}{D} = \frac{532.10^{-9}}{254.10^{-3}} = 2.09.10^{-6} rads$$

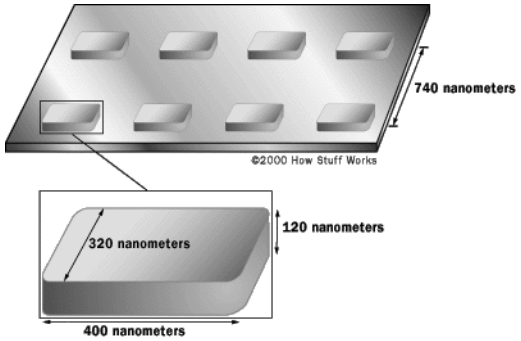
= 0.43 arc-seconds

often used approximation

$$q = \frac{120}{D\,(mm)}$$ arc-seconds

# Diffraction from a CD

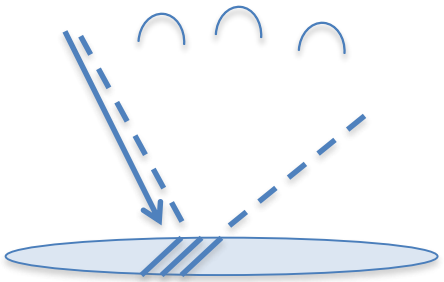


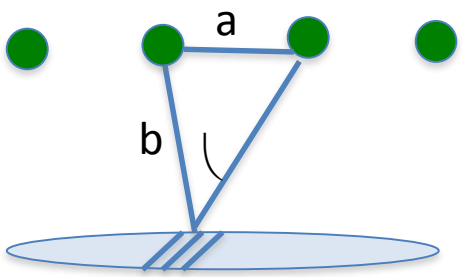




| Type | Capacity | Track Pitch | Wavelength | Colour |
|---|---|---|---|---|
| CD | 0.7 GB | 1.6 μm | 780 nm | Infrared |
| DVD | 4.7 GB | 0.74 μm | 650 nm | Red |
| Blu-ray | 25 GB | 0.32 μm | 405 nm | Blue |
| | | | 532 nm | Green |

$$\sin\theta \approx \frac{l}{D}$$

D=track pitch



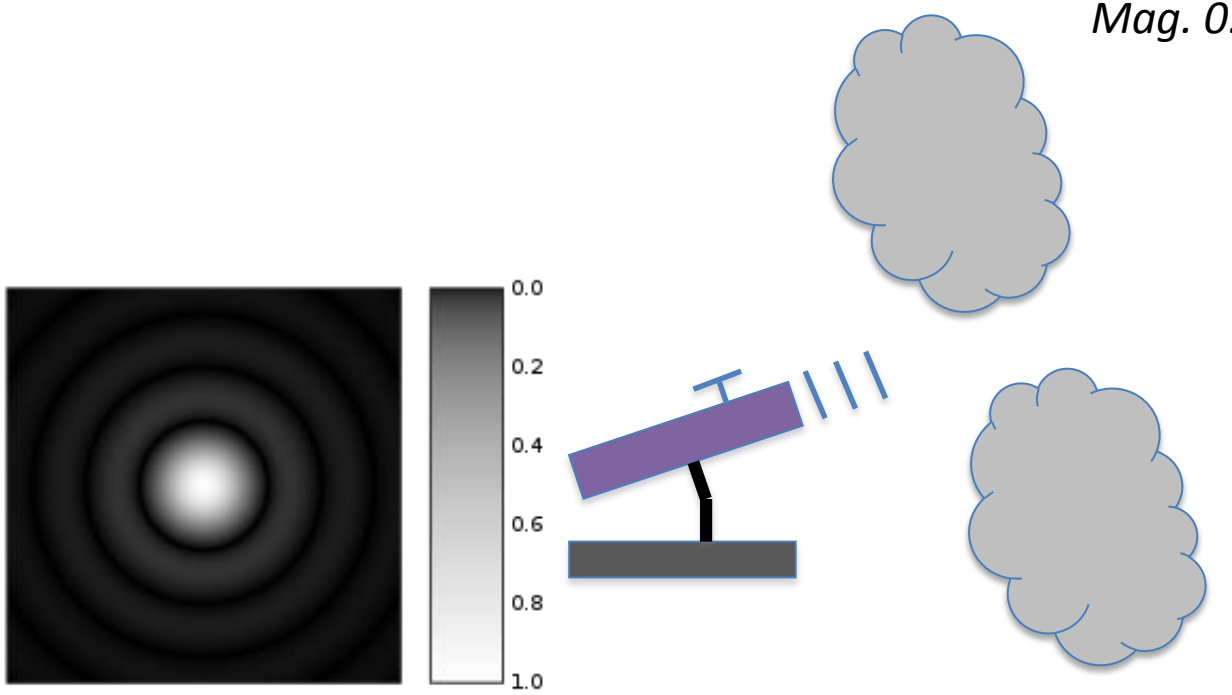



and $\sin\theta \approx \frac{a}{b}$

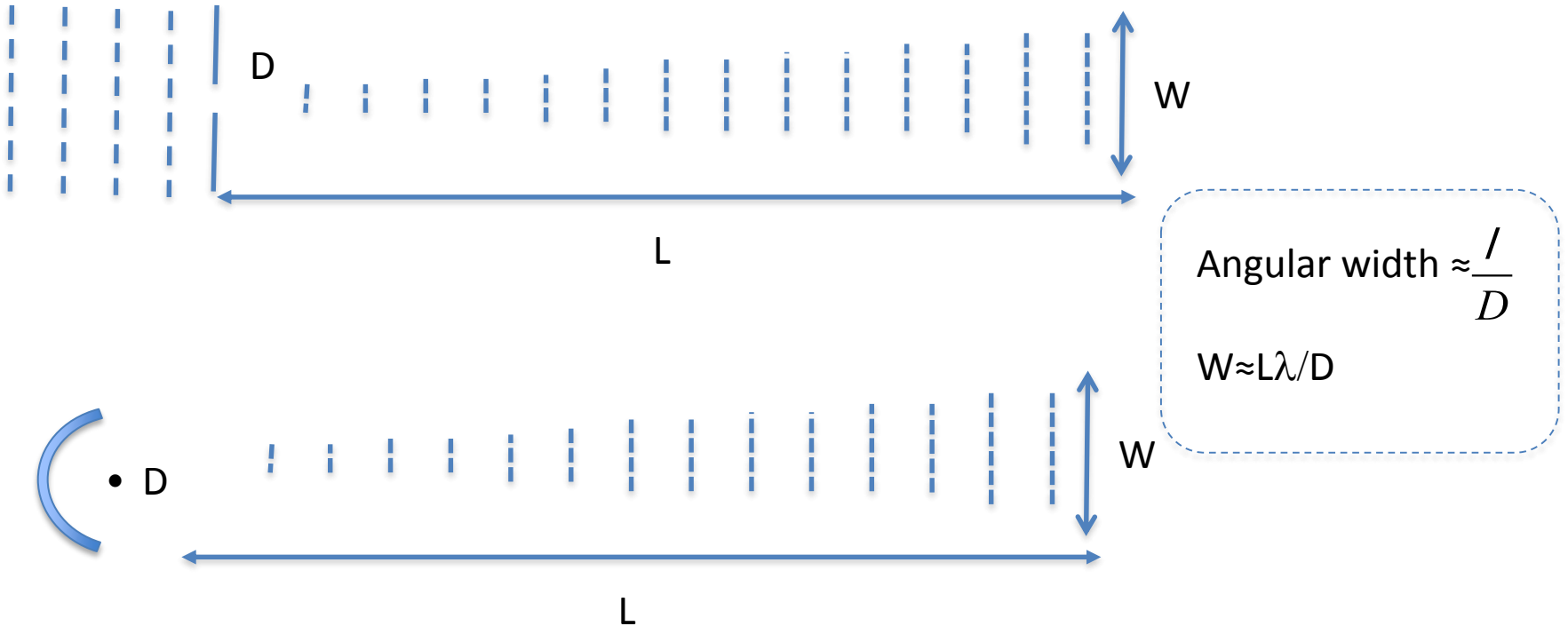
$$D \approx \frac{l\,b}{a}$$

Measure a,b and know wavelength to get D

*Rigel (Beta Orionis)  (900 light years)*
*Mag. 0.18*



# So Remember




All waves undergo diffraction; water waves, sound waves, electromagnetic waves
They diverge according to wavelength and aperture size, with angular width of

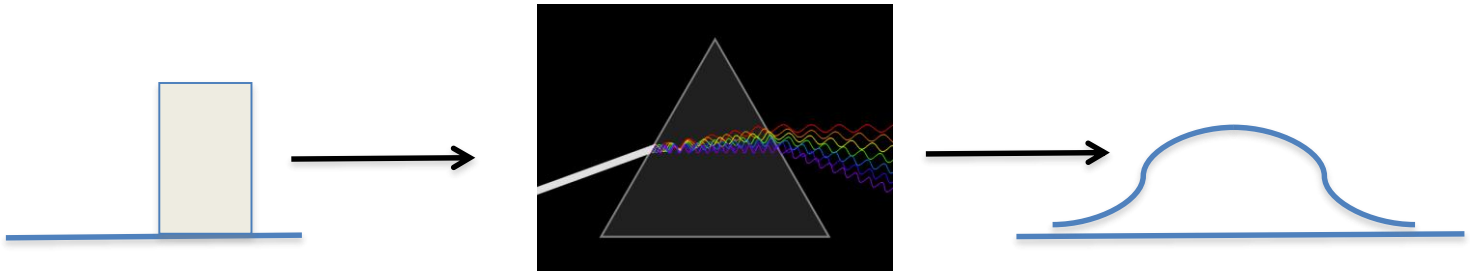
$$\frac{\lambda}{D}$$

# More Exotic Guiding of EM (& Mech) waves

A travelling wave undergoes change in a number of ways.

-it can diminish in amplitude due to losses in the medium or spread of the wavefront

-it undergoes dispersion whereby it loses shape and gradually spreads out (eg surface waves on water (some parts travel faster than others), signals on optical fibre cables)

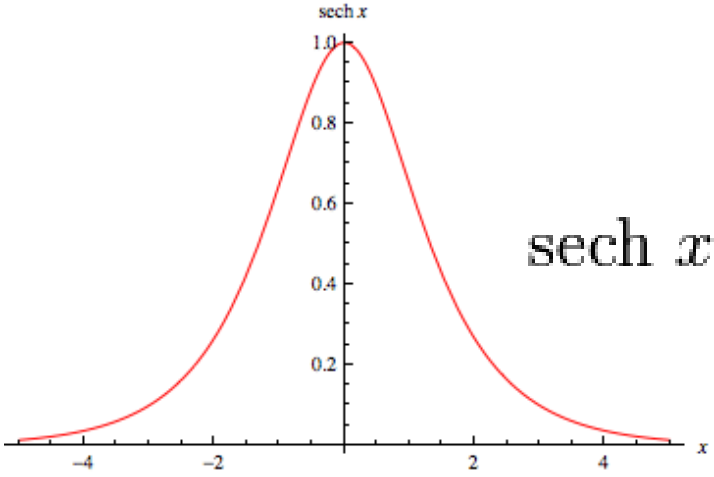


*Some waves "Solitons" have special properties that overcome these characteristics*

# Soliton Waves

In 1834, John Scott Russell describes his wave of translation as a “singular and beautiful phenomenon which I have called “The Wave of Translation”. “The happiest day of my life”


Union Canal (nr Edinburgh)




$$\operatorname{sech} x = (\cosh x)^{-1} = \frac{2}{e^x + e^{-x}} = \frac{2e^x}{e^{2x} + 1}$$

***The soliton wave is a method of warp propulsion that could revolutionize the way spacecraft are powered !!***

Morning Glory cloud formation in QLD, Australia

60 km/hr; 200 m above ground;1000km long
1-8 consecutive clouds

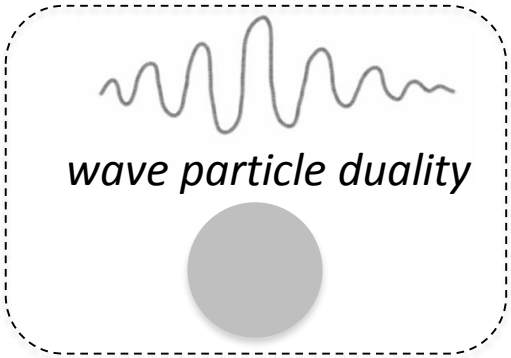

Severn tidal bore

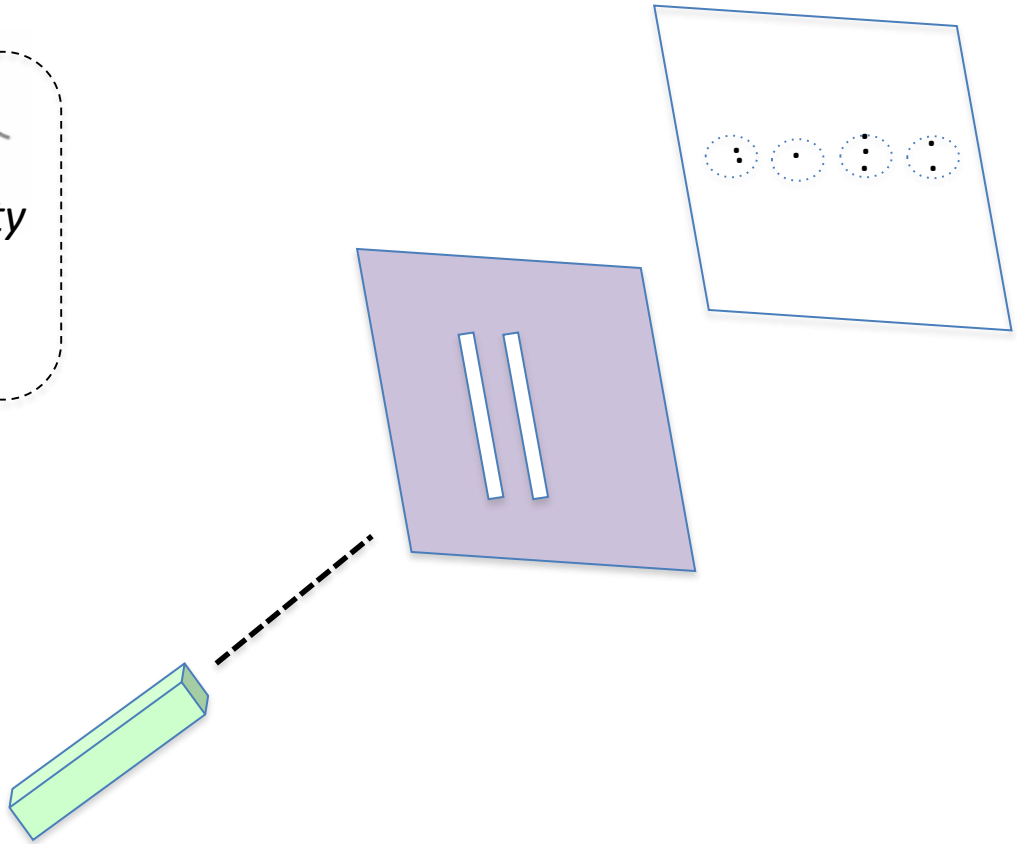
wavefront followed by a train of solitons

High speed optical transmission system using solitons to overcome fibre dispersion

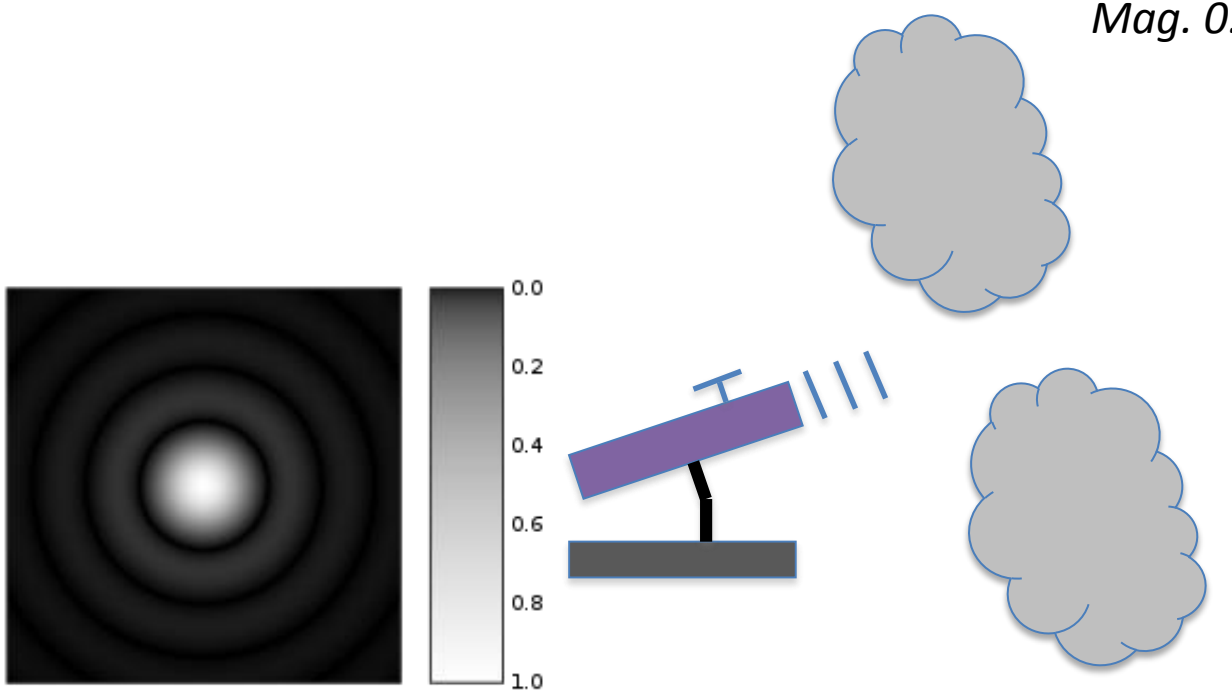

*-The speed depends on the size of the wave, and its width on the depth of water .*
*-If a wave is too big for the depth of water, it splits into two, one big and one small*
*-Taller wave faster than shorter wave, so overtakes, but never merges.*
*-The waves are stable, and can travel over very large distances*

# Two Slit Diffraction



*Rigel (Beta Orionis)  (900 light years)*
*Mag. 0.18*



# We (and All Matter) are Waves

*In 1923 Louis de Broglie proposed that we should think of all matter as waves*

$$l = \frac{h}{mv}$$

h = Planck's constant=6.6 x$10^{-34}$ $m^2.kg.s^{-1}$

m = mass; v= velocity

*h= 6.626x$10^{-34}$ J.s = 0.000000000000000000000000000006626 J.s*

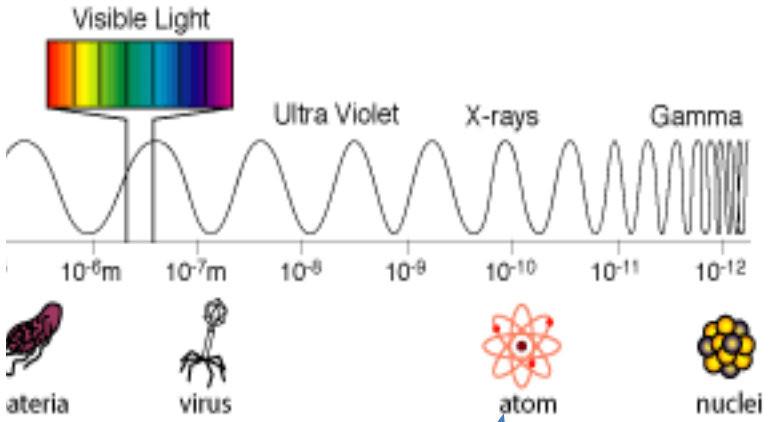
So a 70 kg person walking around can be represented by a wavelength of about 5x$10^{-36}$ m

ie very very small

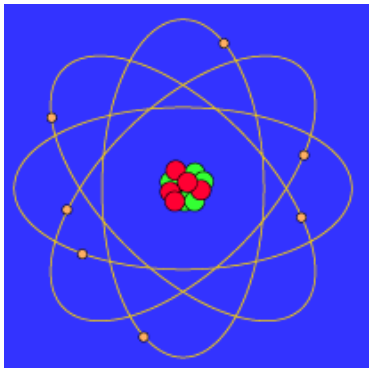
# Electron Waves

**electron mass = 9.1 × $10^{-31}$ kg;  v = 2.19x$10^{6}$ m.$s^{-1}$**

$$l = \frac{h}{mv} = 3.66 \times 10^{-10} \text{ m}$$



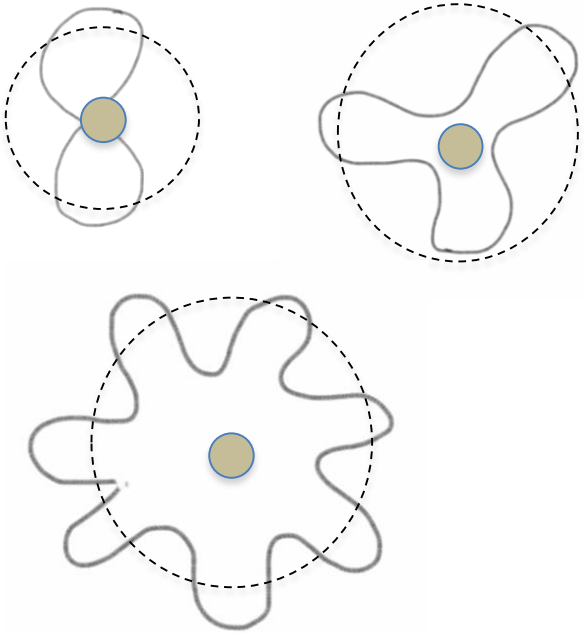

http://stedjee1.infinology.net/Velocity_Orbit_Electron/Velocity%20of%20Orbiting%20Electron.htm



# The Wave Model of Atoms

**Bohr Planetary Model:**

The feature of quantum mechanics that is incorporated in the Bohr Model is that the energy of the particles is restricted to certain discrete values; ie the energy is quantized. Thus only certain orbits with certain radii are allowed; orbits in between simply don't exist.



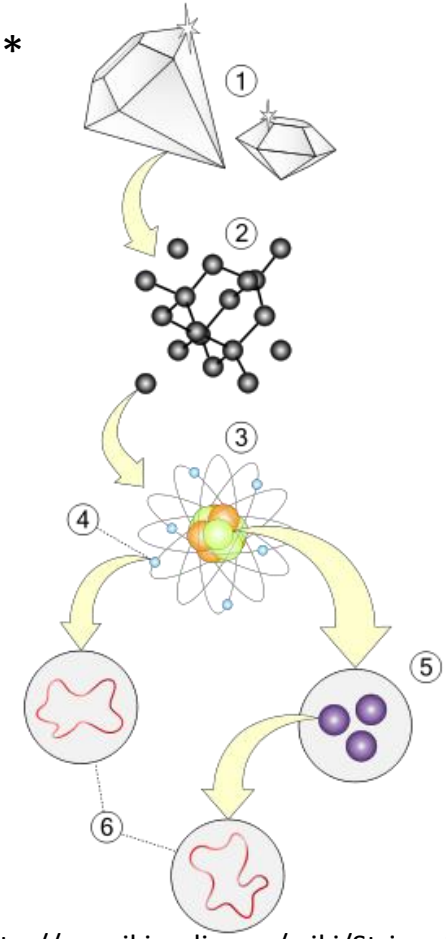
**Wave Model:**

Instead of having a particle moving around the nucleus, we have a wave placed around the nucleus. The only way such a wave could exist is if a whole number of its wavelengths fit exactly around a circle (with nucleus at centre). Greater no. of wavelengths (energy levels), greater diameter of circle.

*Size of nucleus is about 100,000 times smaller than Bohr radius ($5x10^{-11}$ m) ie almost all empty space. Wave model shows that this apparent space not available.*

# Matter and Strings

**




**http://en.wikipedia.org/wiki/String_theory

1. Macroscopic level – Matter
2. Molecular level
3. Atomic level – Protons, neutrons, and electrons
4. Subatomic level – Electron
5. Subatomic level – Quarks
6. String level

-wave theory is being used to try and unify the theory of general relativity and quantum field theory [very large to very small]

-In string theory particles arise as excitations or vibrations on a sting producing wave like patterns. The electron is a string vibrating one way, the quark is a string vibrating another way, and so on.

-the average size of a string should be somewhere near the length scale of quantum gravity, called the **Planck length**, which is about $10^{-35}$ m, this means that strings are way too small to see by current or expected particle physics technology

# String Theory

-Each fundamental particle is not pointlike but instead consists of a -tiny, one-dimensional loop.

-String theory includes both open strings, which have two distinct endpoints, and closed strings making a complete loop.

-In most string theories one of the closed string modes is the graviton, and one of the open string modes is the photon. Because the two ends of an open string can always meet and connect, forming a closed string, there are no string theories without closed strings.

String interactions don't occur at one point but are spread out in a way that leads to more sensible quantum behavior

Particle physics interactions can occur at zero distance -- but Einstein's theory of gravity makes no sense at zero distance.

superstringtheory.com/basics/basic3.html

# The Higgs Boson and String Theory

-The Standard Model of particle physics is incomplete in that to account for the masses of particles it requires the existence of a new field called the Higgs field which is analogous to the electromagnetic field.

-An electromagnetic field is detected by its quanta-photons, and the Higgs field would be detected by its quanta, called Higgs bosons.

-String theory [in 10 dimensions] requires our existing world to have a property called super-symmetry. And a super-symmetric Standard Model incorporating string theory has Higgs bosons and explains their properties.

-Thus finding a Higgs boson strongly supports the supersymmetric Standard Model, which in turn supports the notion of string theory as the unifying theory.

http://www.scientificamerican.com/article.cfm?id=how-does-the-higgs-boson

***So Pythagoras had the right idea 2500 years ago-the world is ruled by waves***

***and remember*** $\frac{l}{D}$