Does Quantum Mechanics Make Sense?

Some relatively simple concepts show why the answer is yes.

Size

Classical Mechanics	Quantum Mechanics
↓	↓
Relative	**Absolute**

What does relative vs. absolute size mean?

Why does it matter?

Classical Mechanics

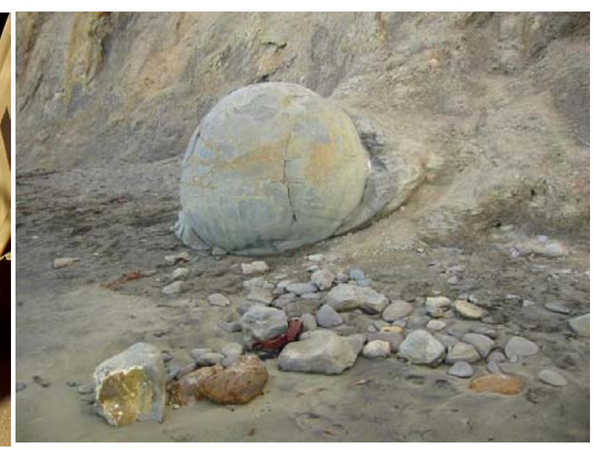
Excellent for: bridges
airplanes
the motion of baseballs

Size is relative.

Tell whether something is big or small by comparing it to something else.

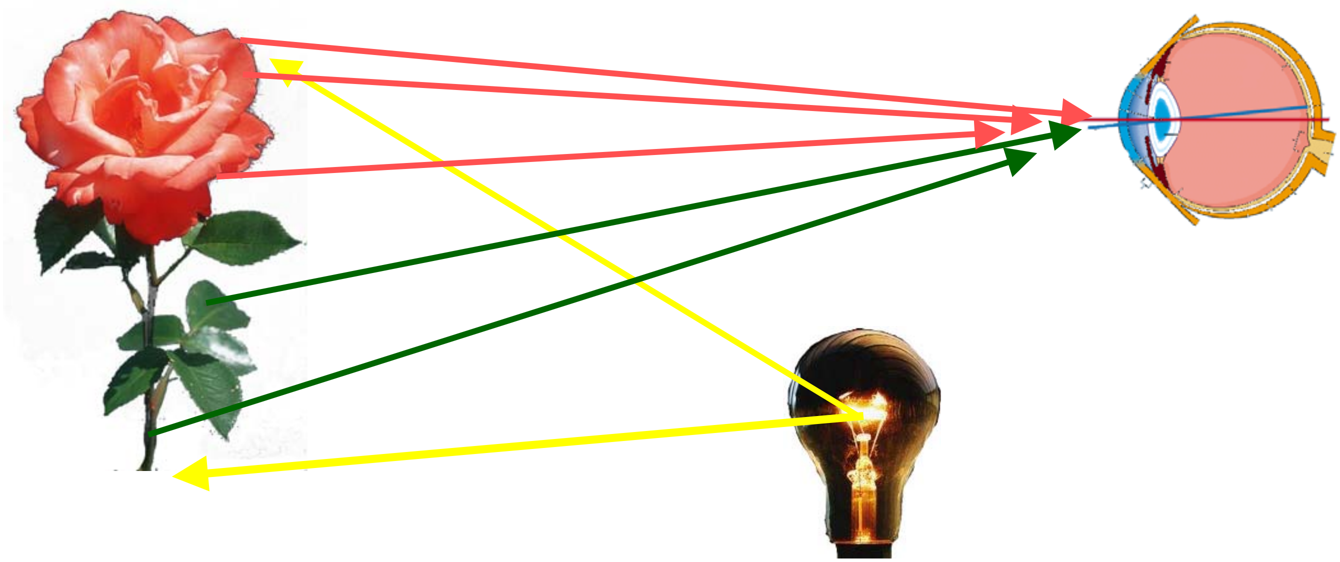
Rocks come in all sizes.

Comparison determines if a rock is big or small.



Why does the definition of size matter?

To observe something, must interact with it.
Always true - in classical mechanics
in quantum mechanics



Light hits flower, "bounces off."
Detect (observe) with eye, camera, etc.

Definition of Big and Small

(Same for classical mechanics and quantum mechanics.)

Disturbance caused by observation (measurement)

negligible → object big

non-negligible → object small

Classical Mechanics

Assume: when making an observation can always find a way to make a negligible disturbance. Can always make object big.

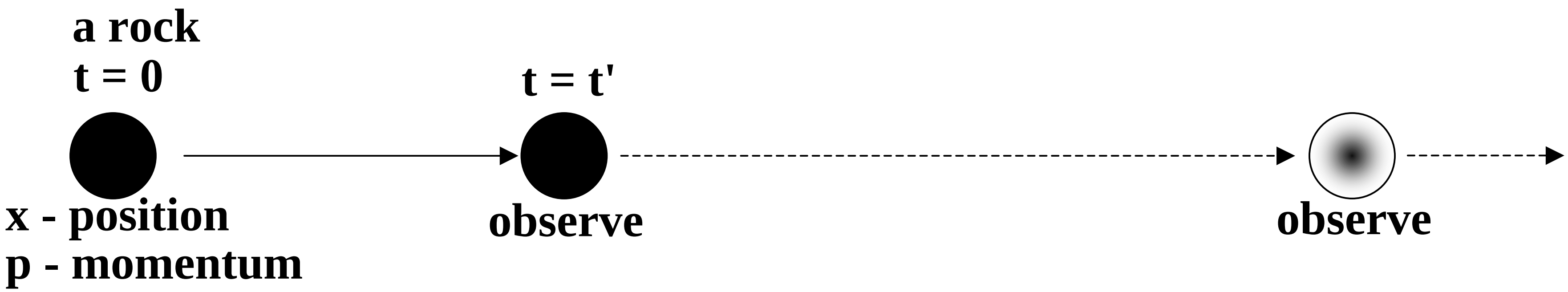
Do wrong experiment → object small.

Do right experiment → object big.

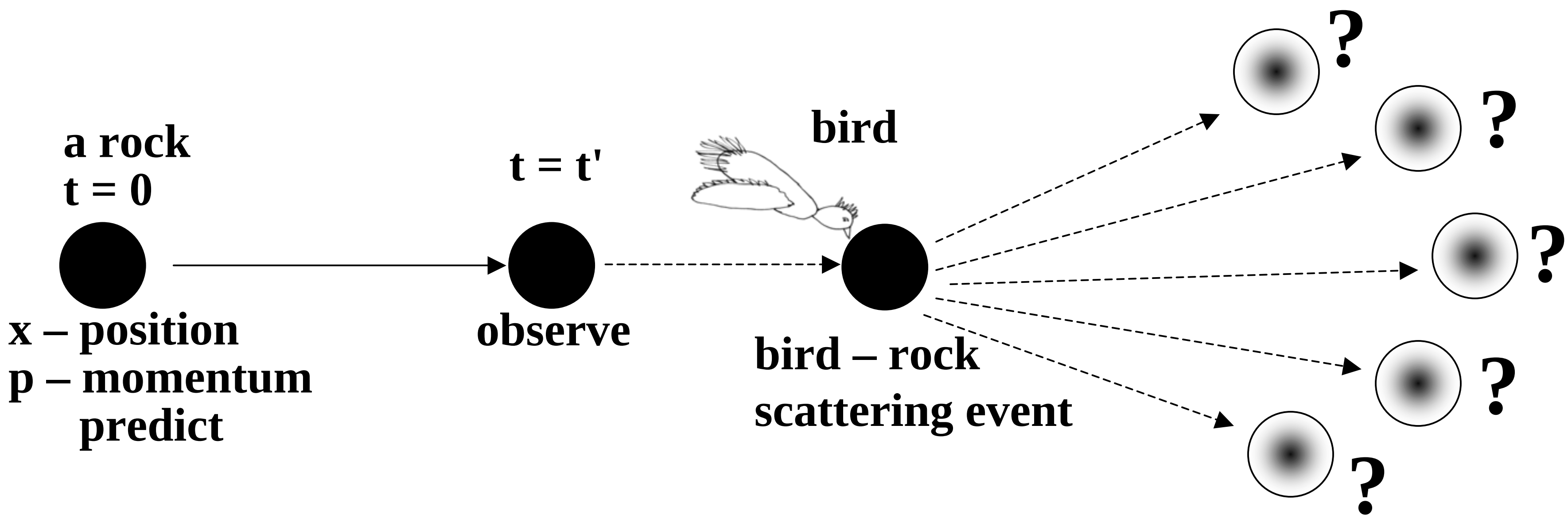
Observe wall with light → big.

Observe wall with bowling balls → small.

Classical, systems evolve with causality.



Make observation of trajectory. Predict future location.



Following non-negligible disturbance – don't know outcome.

Quantum Mechanics
Size is absolute.

Quantum Mechanics is fundamentally different from classical mechanics in the way it treats size.

Absolute Meaning of Size

Assume: **"There is a limit to the fineness of our powers of observation and the smallness of the accompanying disturbance, a limit which is inherent in the nature of things and can never be surpassed by improved technique or increased skill on the part of the observer."**

Dirac

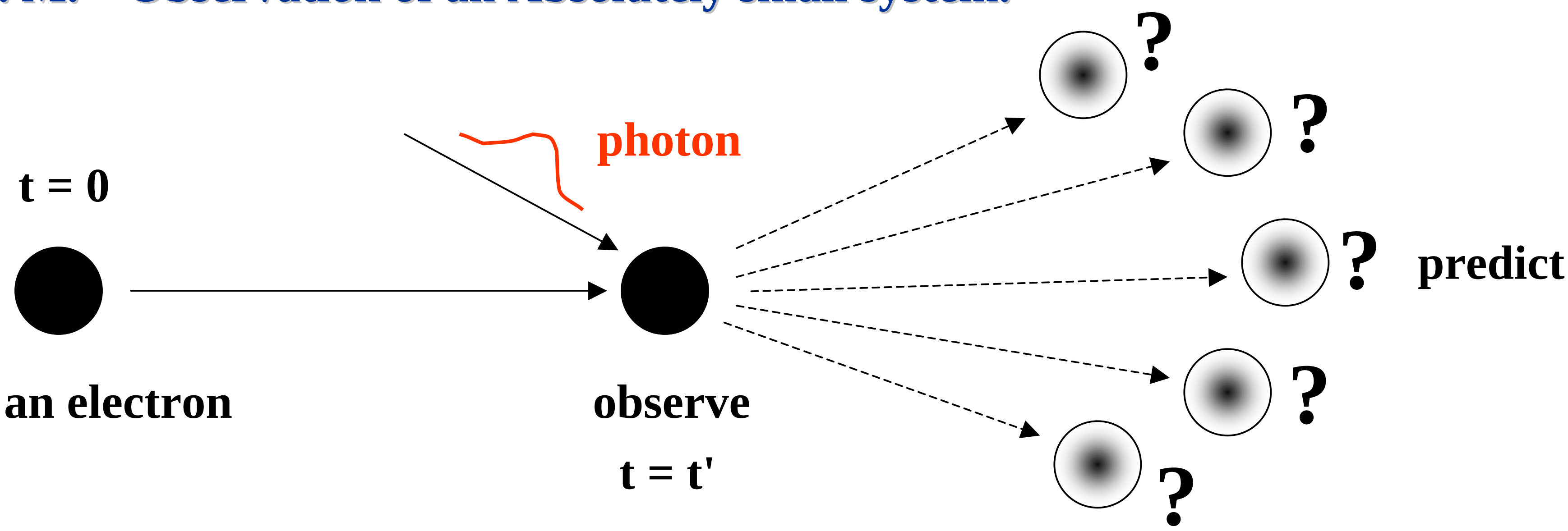
Quantum Mechanics

Big object – unavoidable limiting disturbance is negligible.

Small object – unavoidable limiting disturbance is not negligible.
Object is small in an absolute sense.
No improvement in experimental technique will make the disturbance negligible.

Classical mechanics not set up to describe objects that are small in an absolute sense.

Q. M. – Observation of an Absolutely small system.



Photon – Electron scattering. **Non-negligible disturbance.**
Can’t predict trajectory after observation.

Causality is assumed to apply to undisturbed systems.

You can tell what a system is doing as long as you don’t observe it.

Indeterminacy comes in calculation of observables.
Act of observation destroys causality.
Theory gives probability of obtaining a particular result.

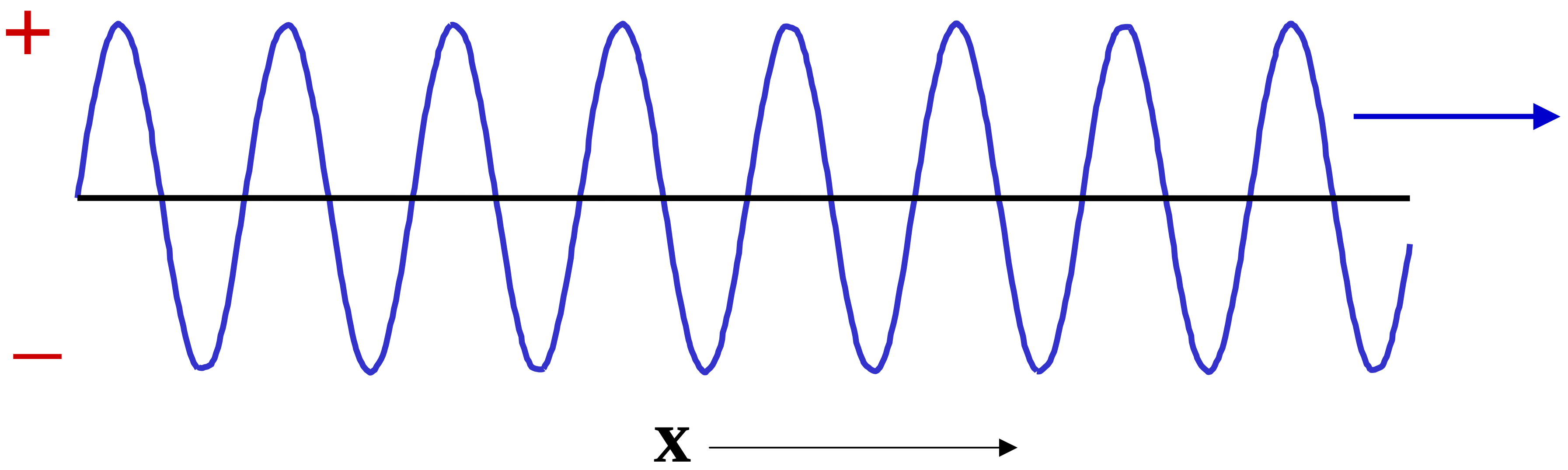
What is the nature of the disturbance that accompanies an observation on a system that is small in the absolute sense?

The explanation gets a little tricky.
To illustrate, first need to talk about waves and their interference.

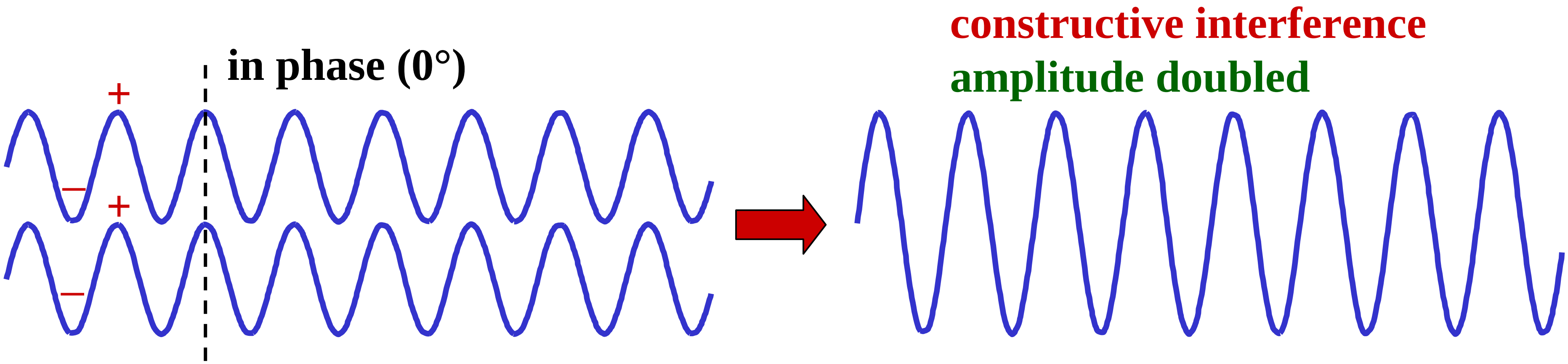
There are many types of waves.

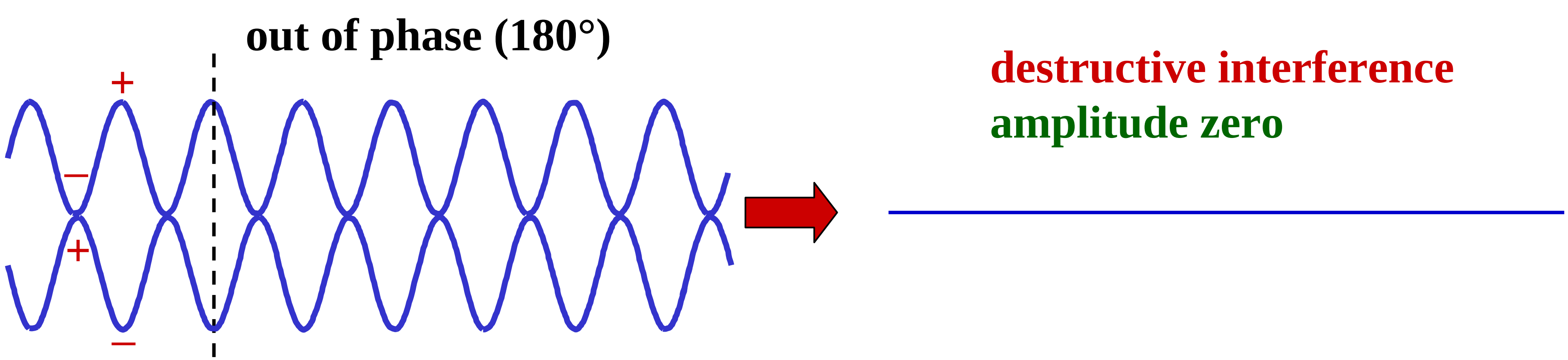
- **water waves**
- **sound waves**
- **electro-magnetic waves**
- **QM probability amplitude waves**

Waves oscillate positive and negative and travel



Waves can be added.





Interference of light – described classically by in terms of light waves (Maxwell's Equations).

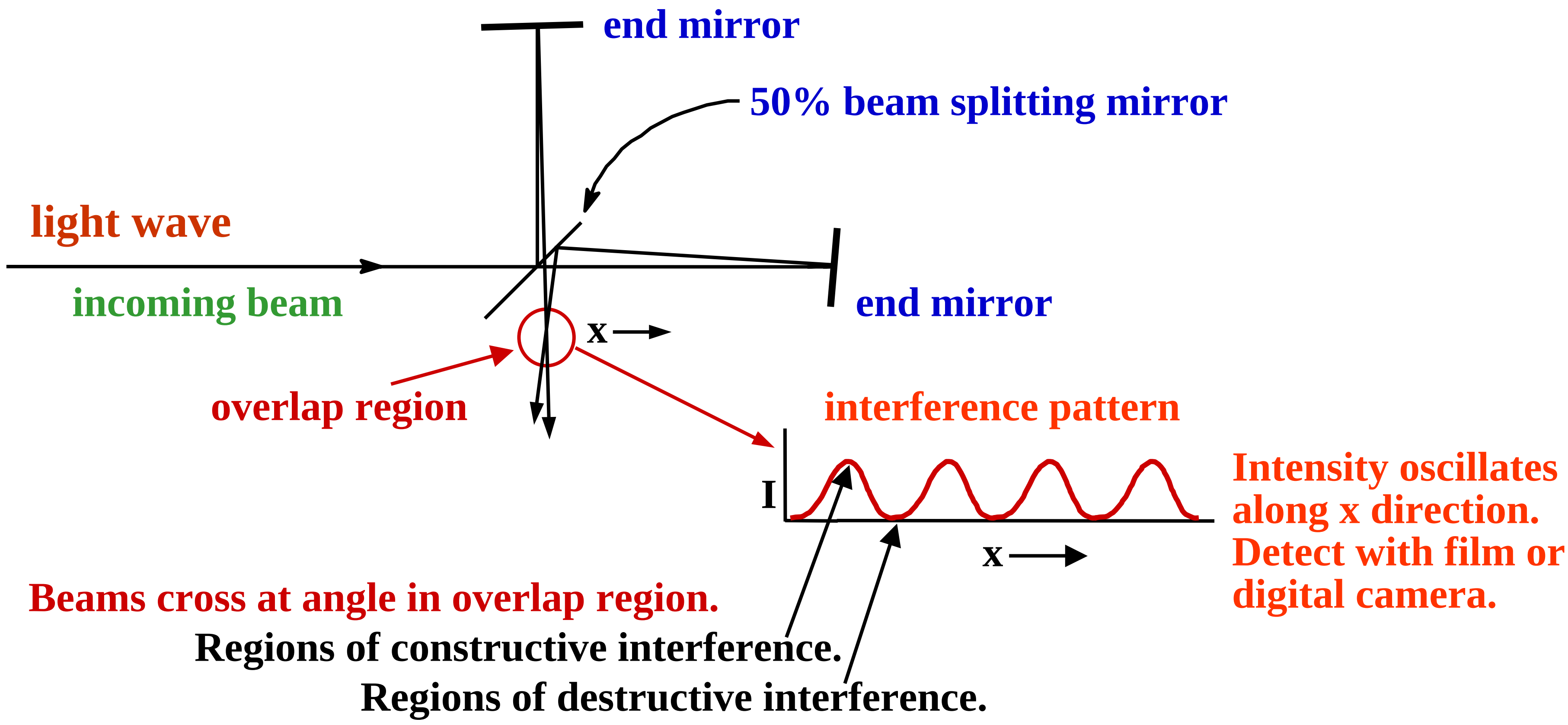
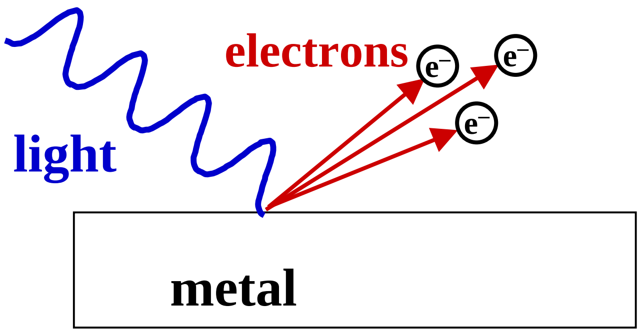


Photo-electric Effect – Classical Theory – Light is a wave.

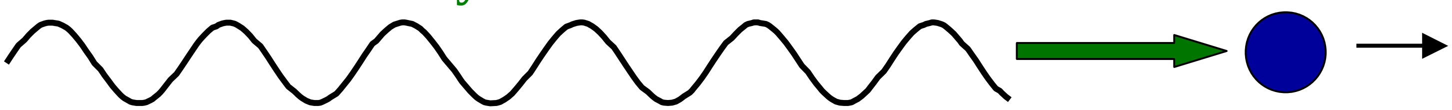


Shine light of one color on metal –
electrons come out with a certain speed.

Increase light intensity
get more electrons out with <u>identical speed</u>.

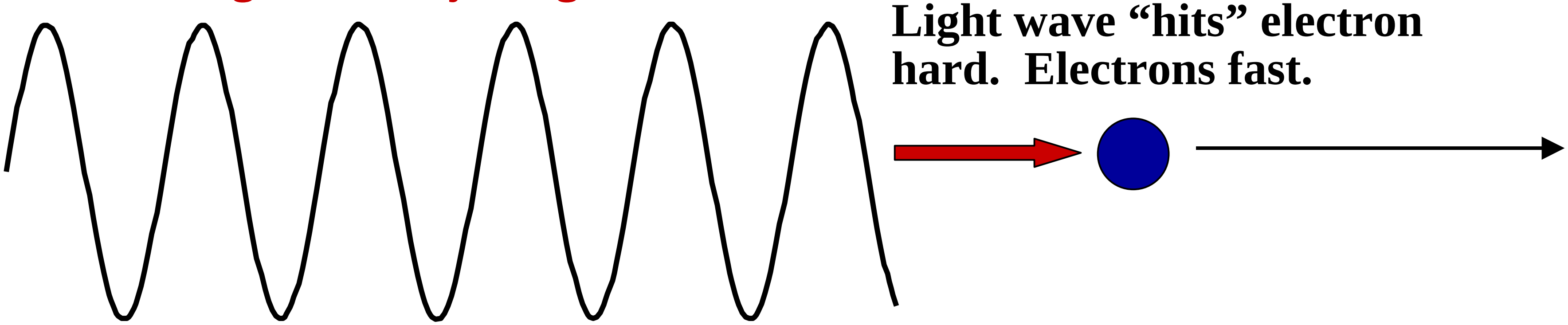
Low Intensity - Small Wave

Light wave "hits" electron
gently. Electrons slow.



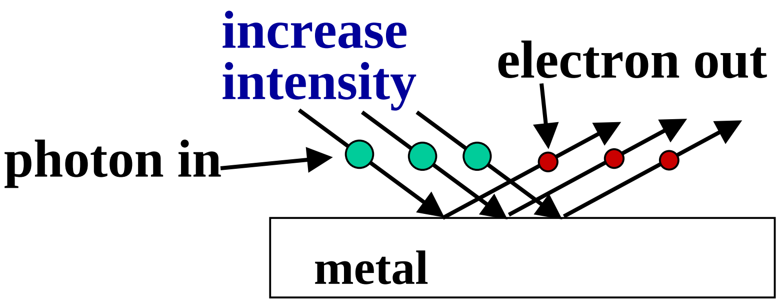
High Intensity - Big Wave

Light wave "hits" electron
hard. Electrons fast.



Einstein explains the photoelectric effect (1905)

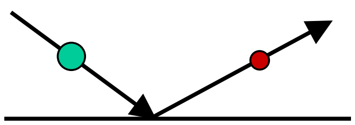
Light is composed of small particles – photons.



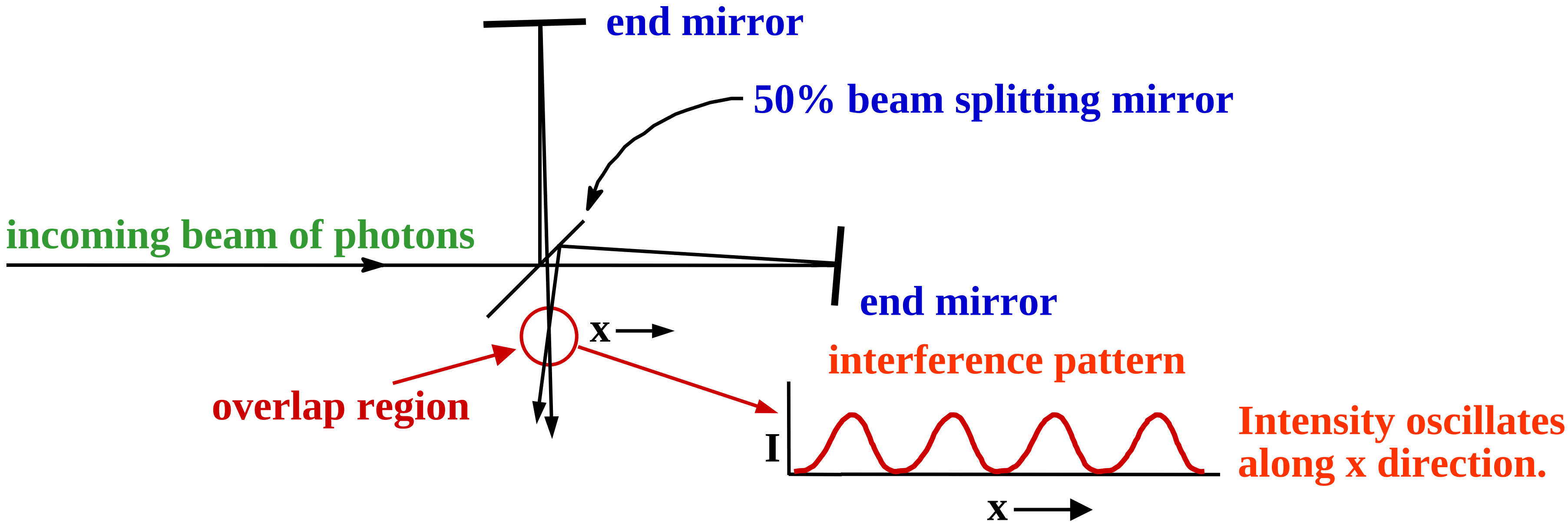
One photon hits one electron.

Increase intensity – more photons,
more electrons hit – more come out.

Each photon hits an electron with same impact
whether there are many or few.



Therefore, electrons come out with same speed
independent of the intensity.

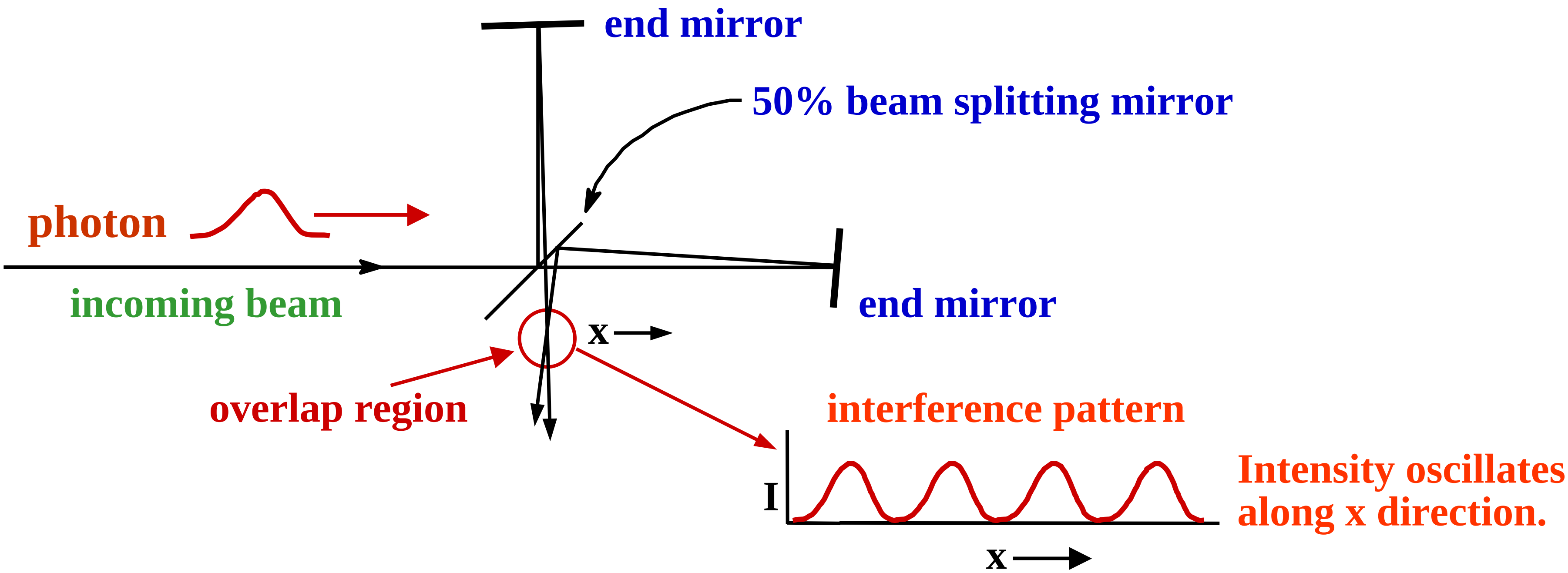


Initial idea:

Classical E&M tried to modify description in terms of photons.

Photons enter interferometer. At beam splitter, half go into one leg, half go into the other leg.
They come together and interfere.

Many problems with this description.
Example: interference pattern unchanged when light intensity approaches zero.



Explanation: each single photon goes into both legs of the apparatus.
Photons are composed of probability amplitude waves, not physical waves.
Make measurement of location in either leg, interference pattern vanishes.

Interference of photons: photon as waves – probability amplitude waves
Photoelectric effect: photons as particles

Need to know about the nature of the probability amplitude waves, how they combine, and what happens when you make a measurement.

State of definite momentum – *p* – for a free particle.

A free particle, a photon, an electron, a rock, is the simplest system.

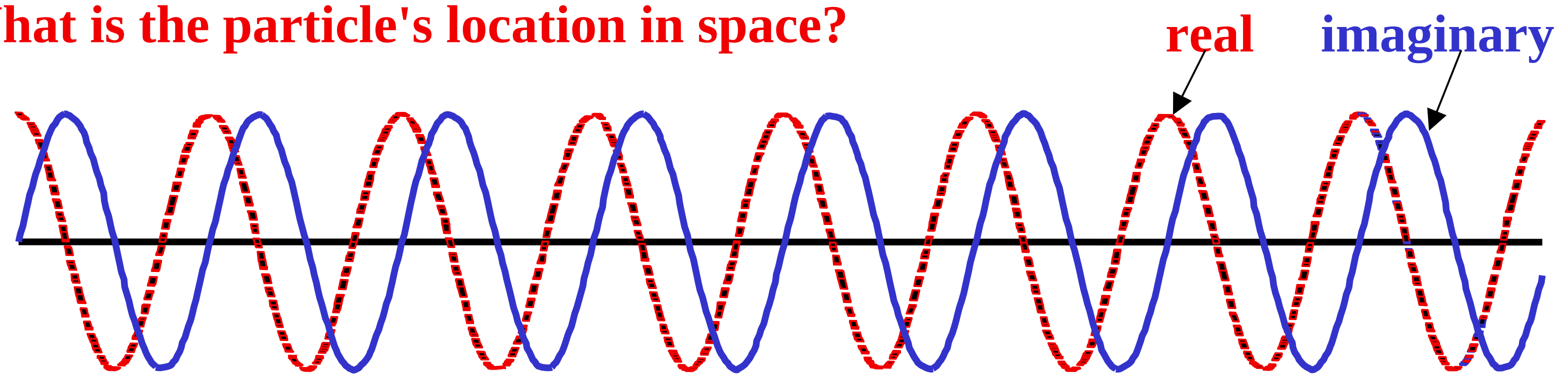
A free particle is a particle moving without any forces acting on it, no electric or magnetic fields, no gravity, etc.

Photon with perfectly defined momentum *p*, (momentum eigenstate) has a wavelength of its probability amplitude wave; so does an electron (de Broglie).

$$p = h/\lambda$$

λ - wavelength; h – Planck's constant $(6.6 \times 10^{-34}$ J-s)

What is the particle's location in space?



Not localized → Spread out over all space.

Equal probability of finding particle from $-\infty$ to $+\infty$.

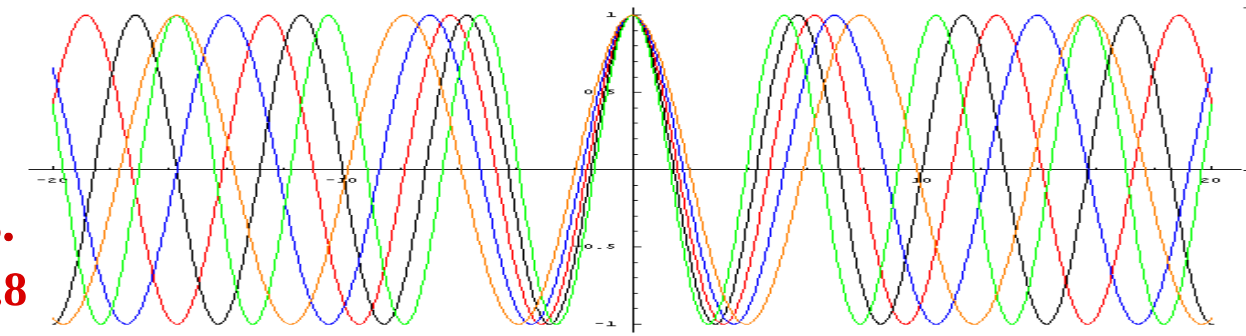
Know momentum exactly → No knowledge of position.

Classical – can know momentum *p* and position *x* exactly at the same time.

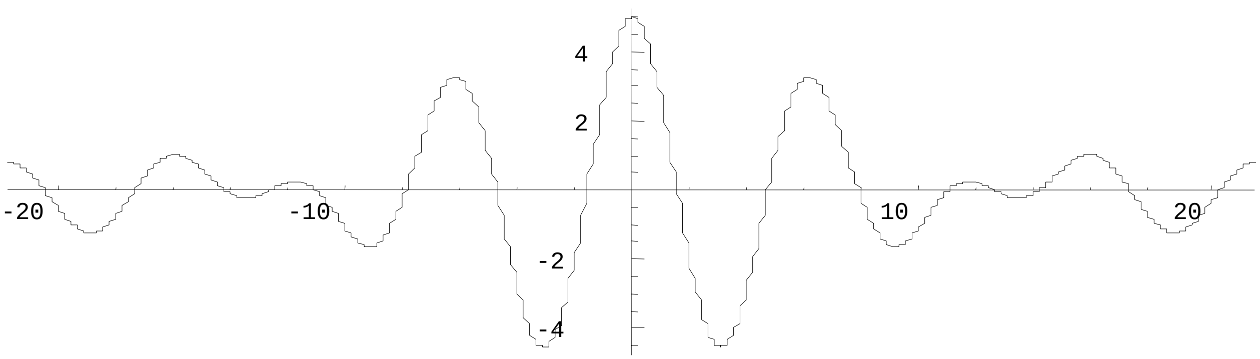
Quantum – know *p* exactly, *x* completely uncertain. Equal probability of finding particle anywhere.

What about Einstein's photons that are particles and electrons that are particles, but they both have momenta that are delocalized probability waves?

Waves of different wavelengths can be added. Add 5 waves.
$\lambda = 1.2, 1.1, 1.0, 0.9, 0.8$



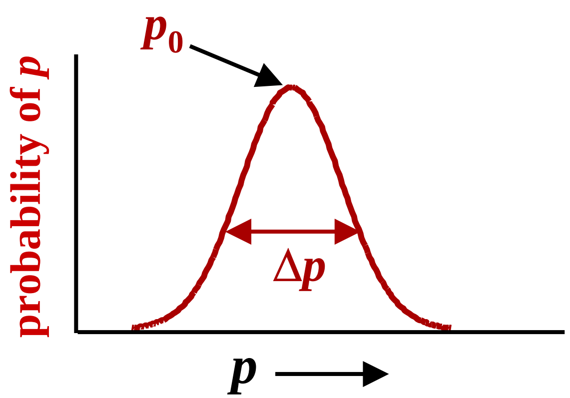
Superposition
Sum of the 5 waves



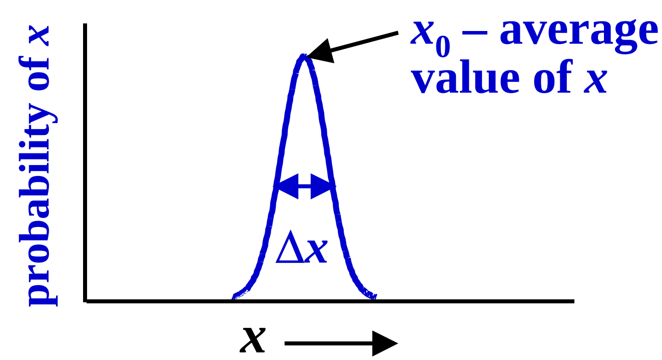
Superimposing 5 waves concentrates probability in a region of space, but now there are 5 values of the momentum.

Wave Packets – add many momentum probability waves together.

Photons and electrons are superpositions of a vast number of momentum eigenstates each with momentum definite p.
The superposition is about some average value, p_0.



What is the spatial distribution of the wave packet with width, Δp?



Added many waves.
Have spread in p, Δp.

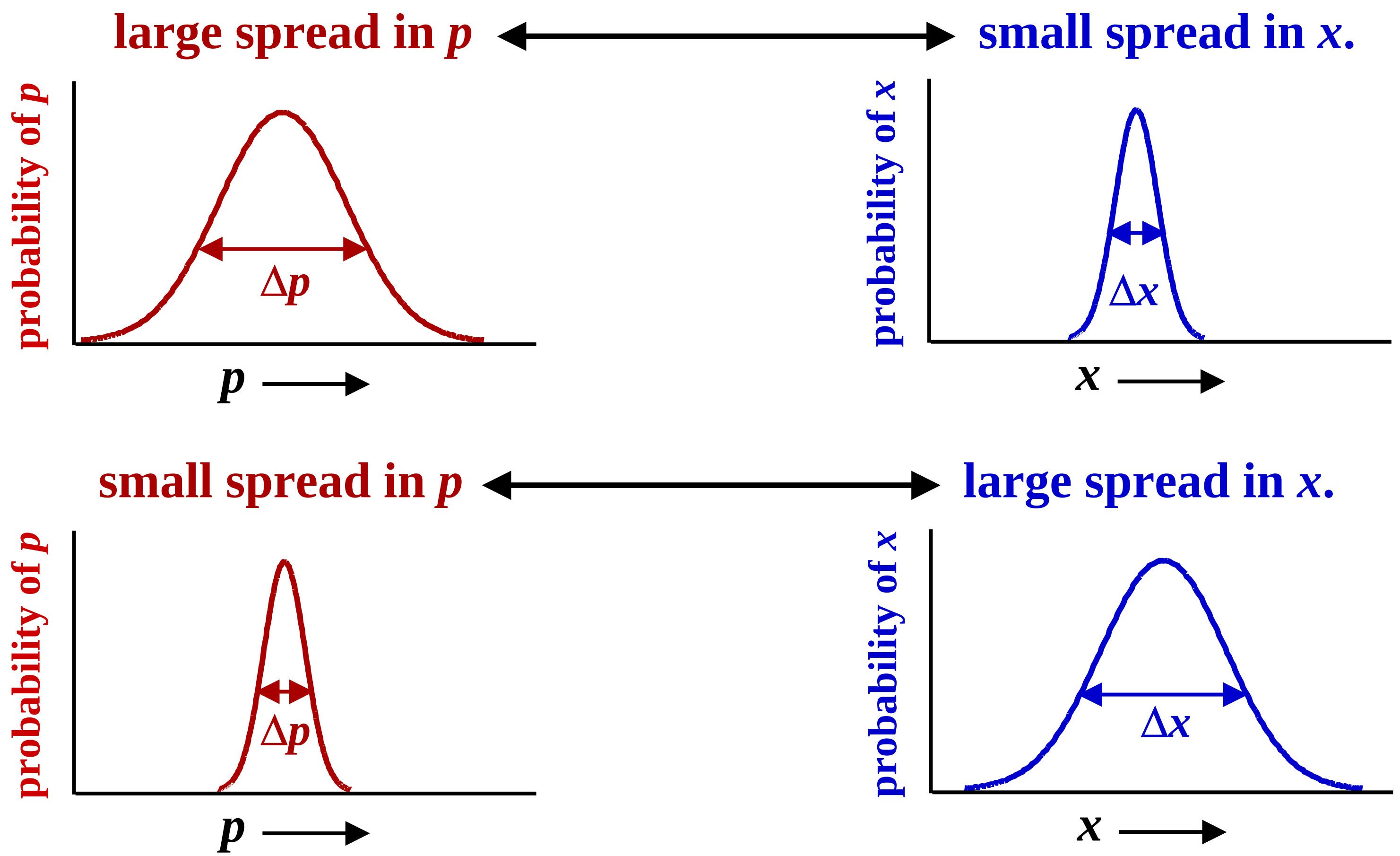
In a measurement, will measure one particular value of p.

The disturbance accompanying a measurement takes system from superposition state into a momentum eigenstate with a particular value of the observable, p.

Packet not spread out over all space like a single momentum eigenstate.
More or less localized with width, Δx .

In a measurement, will measure one particular value of x.

The disturbance accompanying a measurement takes system from superposition state into a position eigenstate with a particular value of the observable, x.



You can know the momentum and position more or less.
The more well defined one is the less well defined the other is.

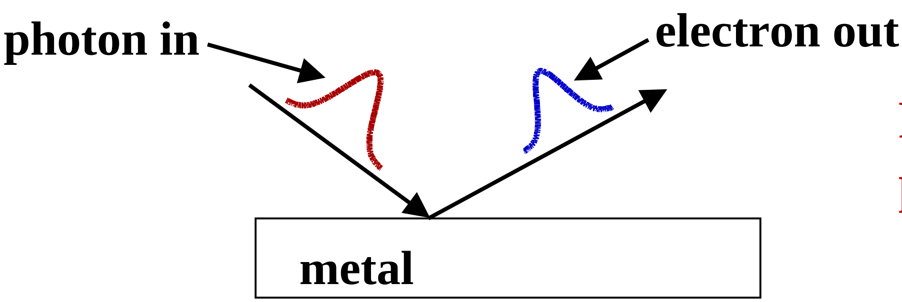
QM Complementarity – can know *p* or *x*, but not both at the same time.
Heisenberg Uncertainty Principle - $\Delta p\ \Delta x \geq h/4\pi$.

Classical Mechanics – can know *p* and *x*.
Quantum Mechanics – can know *p* or *x* (absolute size).

Wave packets act as particles or waves depending on the measurement.

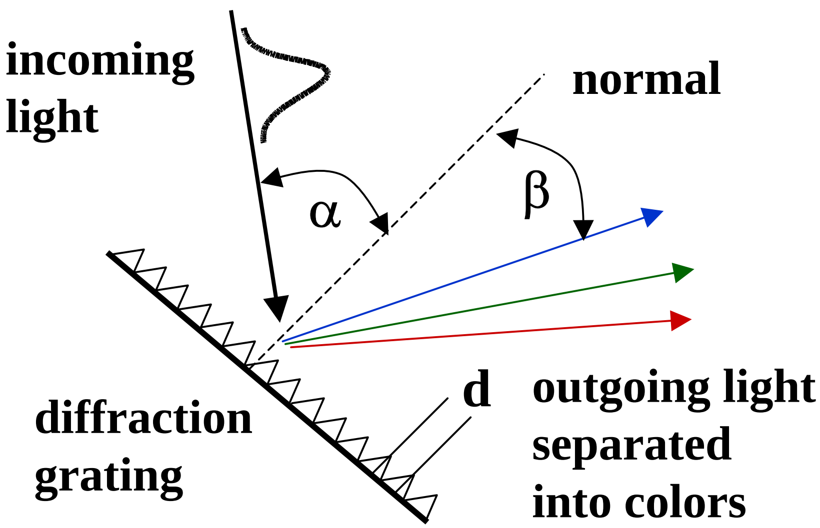
Light – photon wave packet, superposition of many *p* states with wavelengths, λ.

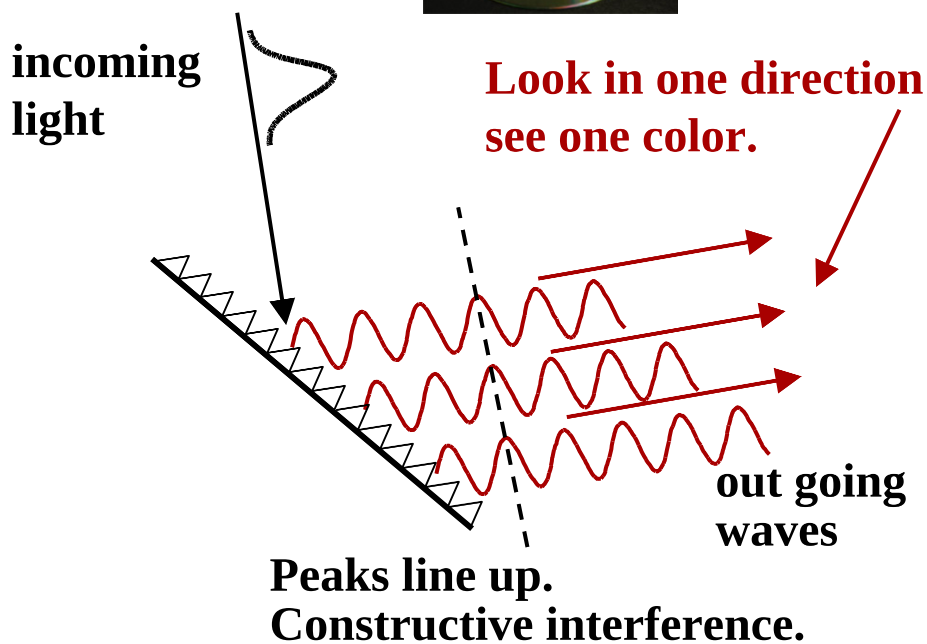
Photons act like particles



Photoelectric effect
photon acts like particle

Photons act like waves – color separation by diffraction

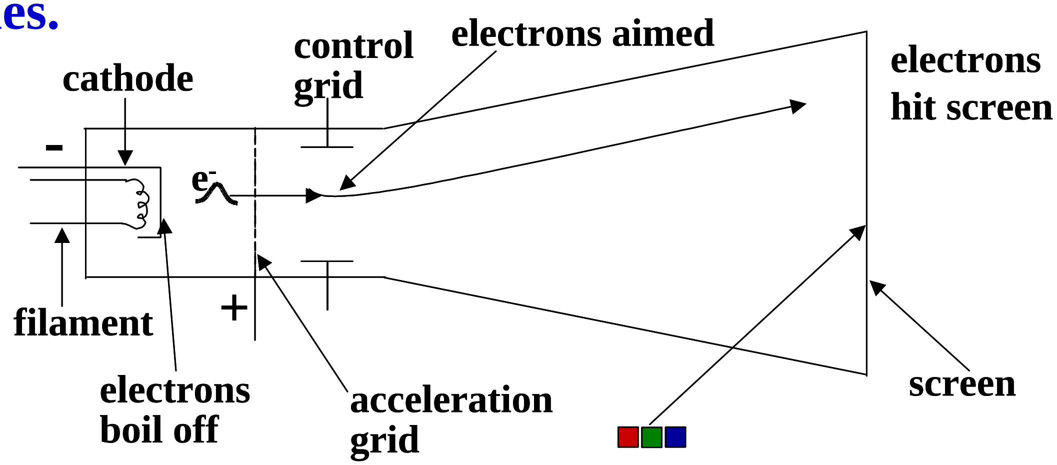




Electrons are wave packets too, as are all other non-zero rest mass particle.

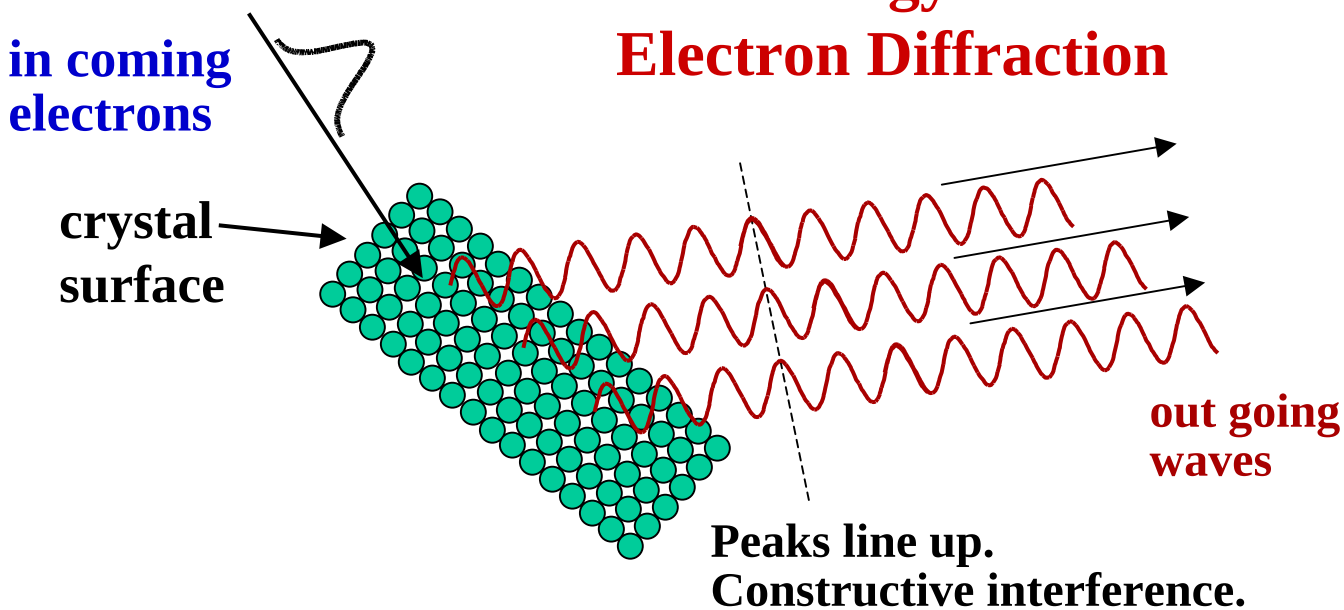
Electrons act like particles.

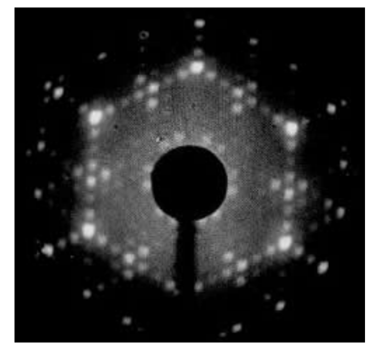
CRT
cathode ray tube
TVs and
computer monitors



Electrons act like waves.

Low Energy Electron Diffraction

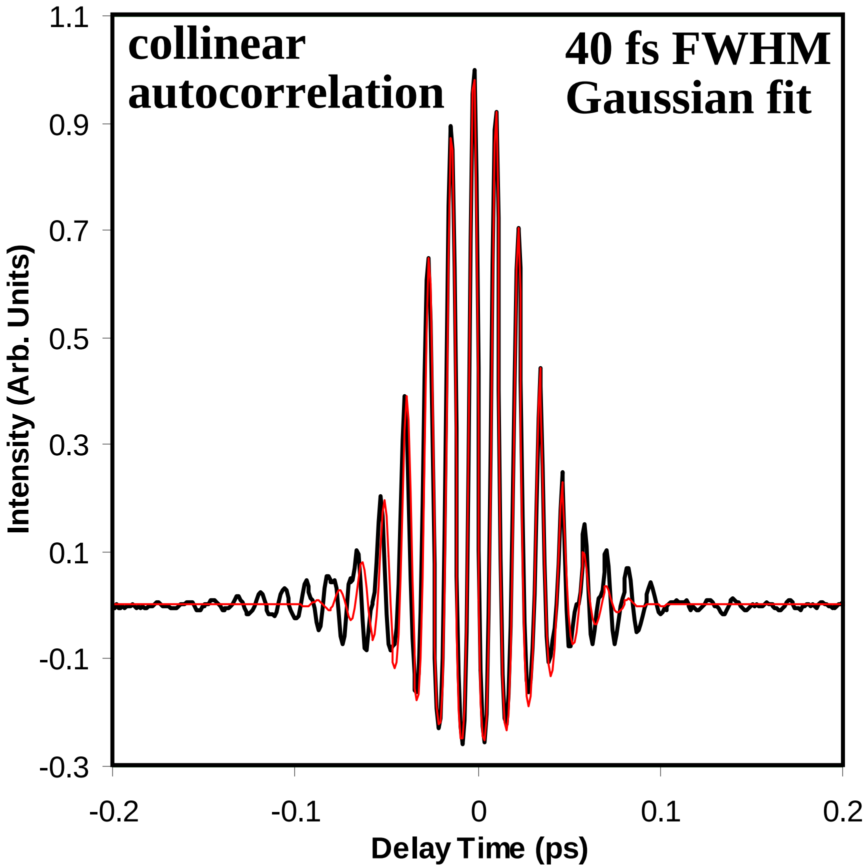


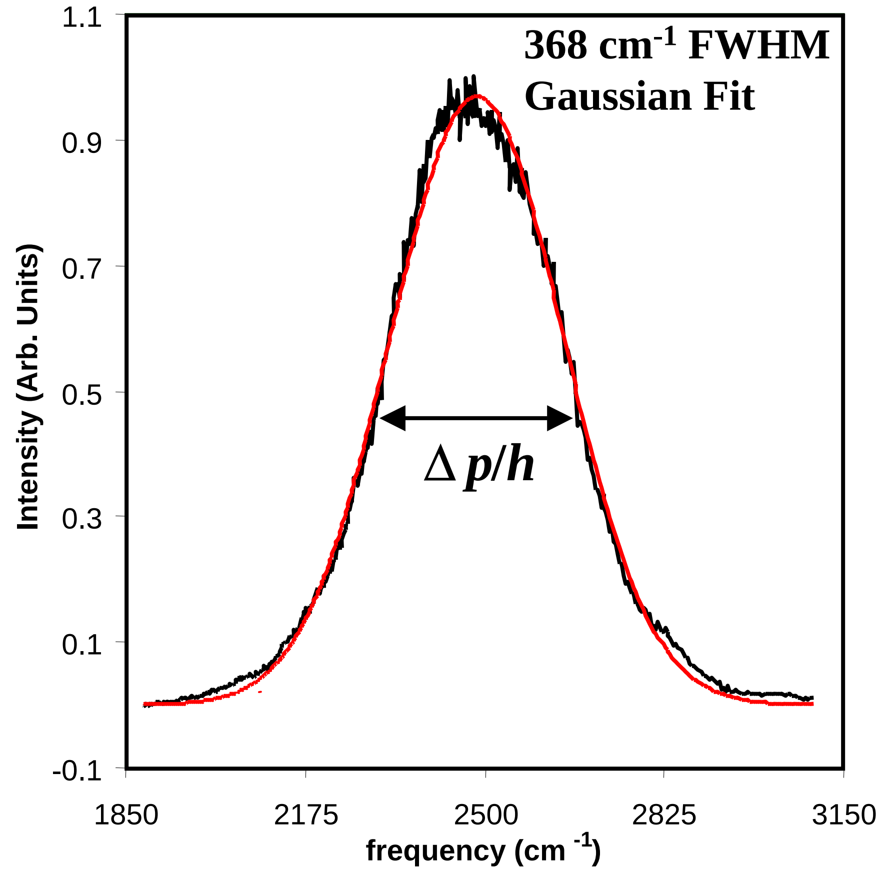


LEED diffraction pattern

Observing Photon Wave Packets

World's shortest mid-infrared optical pulses





$$\Delta t = 40 \text{ fs} = 40 \times 10^{-15} \text{ s}$$

$$\Delta x = c\Delta t$$

$$\Delta x = 1.2 \times 10^{-5} \text{ m} = 12\,\mu\text{m}$$

$$p = h/\lambda \qquad \lambda^{-1} = p/h$$

$$\Delta p = 2.4 \times 10^{-29} \text{ kg-m/s}$$

$$p_0 = 1.7 \times 10^{-28} \text{ kg-m/s}$$

Example – electrons exhibit wave-like properties, baseballs don't. Why?

Electron $\lambda = \frac{h}{p}$ $h = 6.6\times10^{-34}$ J-s

$p = mv$ $v = 5.0\times10^{6}$ m/s $m_e = 9.1\times10^{-31}$ kg

typical velocity of an electron in an atom

$$\lambda = \frac{6.6\times10^{-34}}{\left(9.1\times10^{-31}\right)\left(5.0\times10^{6}\right)} = 1.5\times10^{-10}\ \text{m} = 1.5\ \text{Å}$$

De Broglie wavelength for an electron in an atom – λ = 1.5 Å, the size of an atom. Wave characteristics important – wavelength size of object.

Baseball m = 200 g v = 30 m/s

$$\lambda = 1.1\times10^{-34}\ \text{m} = 1.1\times10^{-24}\ \text{Å}$$

The wavelength is 18 orders of magnitude smaller than the size of a single nucleus. Wavelength negligible compared to size of object. Undetectable.

These are the basic concepts of Quantum Mechanics

Absolute Size
Superposition Principle
Complementarity

Quantum mechanics is necessary to describe systems on the size scale of Molecules, Atoms, and smaller.

QM also has fundamental impacts on aspects of the universe on all size scales as you are about to see.

This presentation can be obtained on my web site
http://www.stanford.edu/group/fayer
or Google Fayer