Part 1: Waves as Particles - The Photon

Aims of Part 1

- To take a brief historical tour of the competing **wave** and **particle** pictures of **light**.

- Consider evidence from **interference experiments** that light is a **wave.**

- Consider evidence that indicate that light is **not a wave**.

- To introduce the **photon**,

    - and by studying **interference experiments** learn that light can be neither completely **wave-** or **particle-like.**

- And thus see the need for a **new physical theory** - **quantum mechanics**.

Light: A wave or a particle?

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Ole Rømer

- ***Rømer: 1676***
    - Light has finite speed - but what is moving?

Images from Wikipedia

Light: A wave or a particle?

Ole Rømer

Christiaan Huygens

- ***Rømer: 1676***
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- ***Huygens: 1678***
  - Light is a wave

Images from Wikipedia

Light: A wave or a particle?

Ole Rømer

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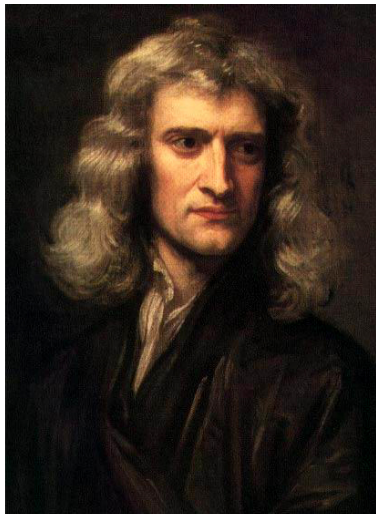

Isaac Newton

Images from Wikipedia

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    - Light is a particle

Light: A wave or a particle?

Ole Rømer

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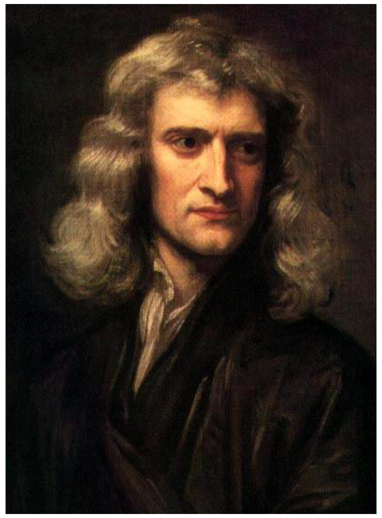


Isaac Newton

Images from Wikipedia

- ***Rømer: 1676***
  - Light has finite speed - but what is moving?
- ***Huygens: 1678***
  - Light is a wave
- ***Newton: 1704***
  - Light is a particle
- ***Both theories could explain:***
  - Finite light speed
  - Shadows
  - Reflection
  - Refraction

The difference between particles and waves?

The difference between particles and waves?

Interference!

The clincher? Young's Double-slit experiment

Thomas Young

- 1800s - If light is a wave, **interference effects** will be measurable.
- 1803 - Proposed **Double Slit Experiment**.

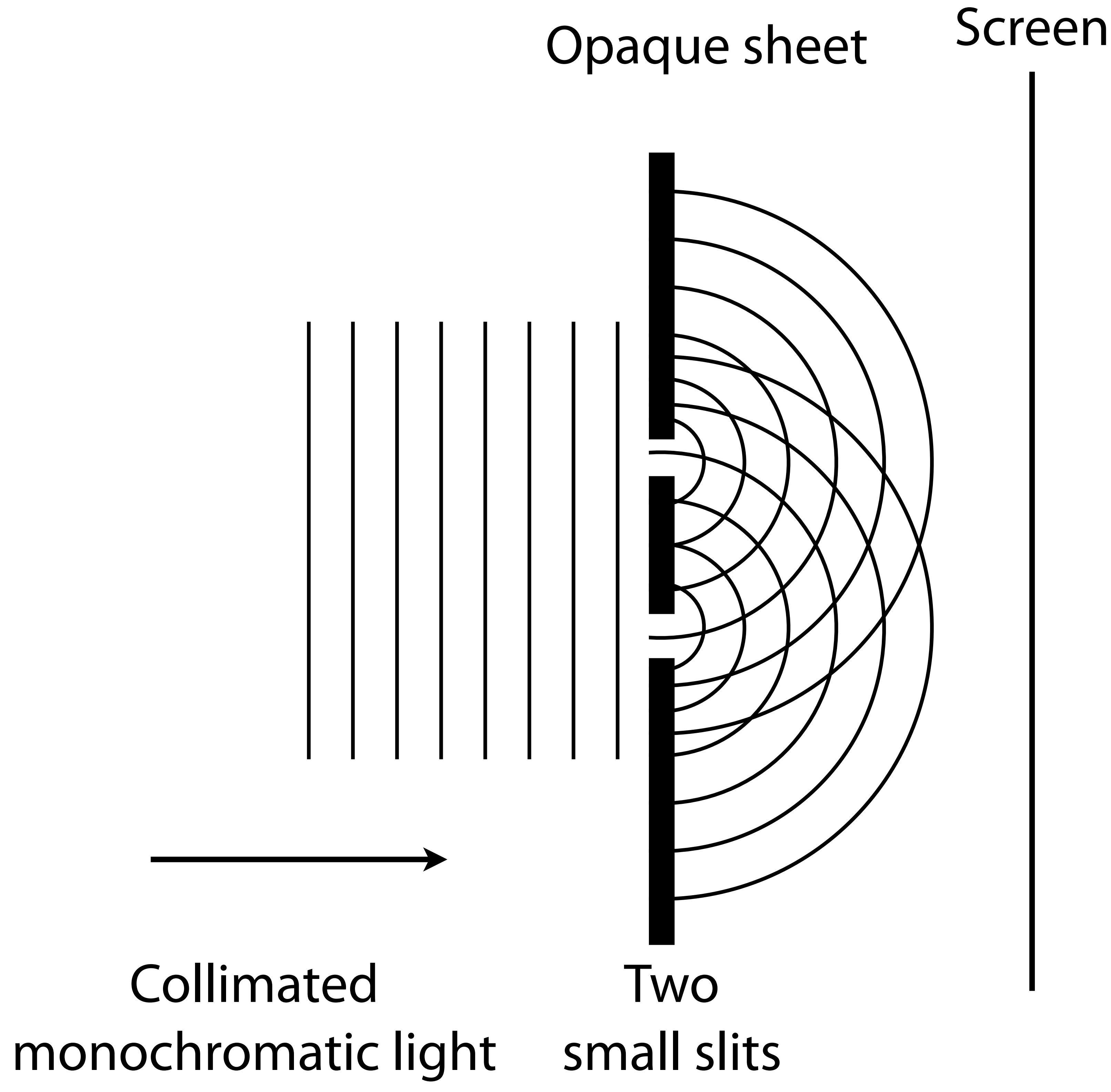
Poll

- Have you studied Young's Double-slit experiment before?

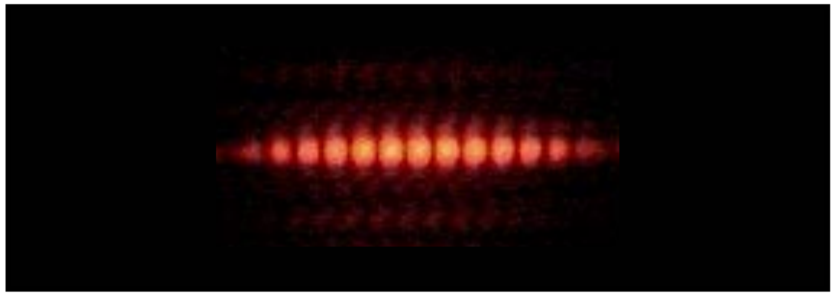
Young’s Double-slit experiment

Details: Jewett and Serway, Chapter 37

T. Young



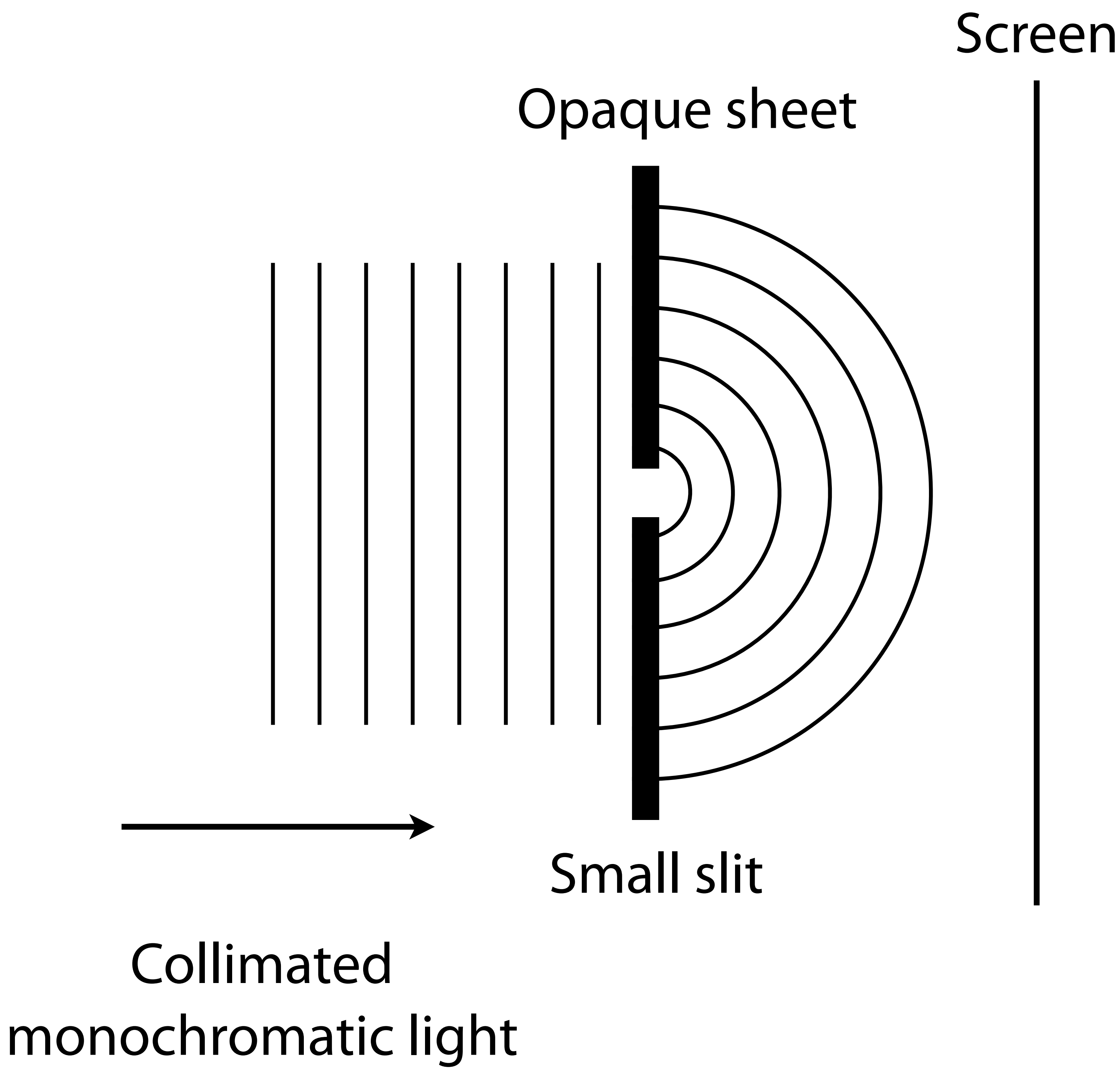
What we observe on the screen



Young's Double-slit experiment

- If we **block one slit:**

T. Young



What we observe
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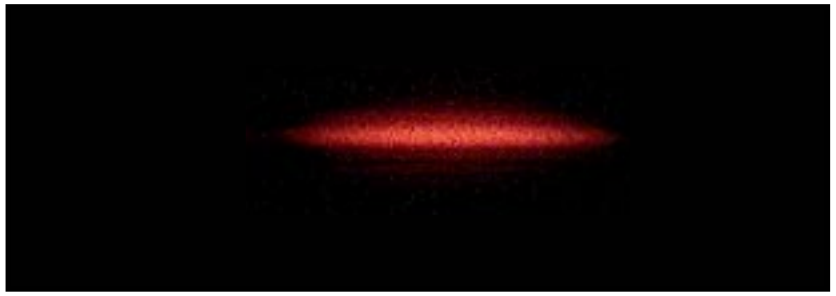
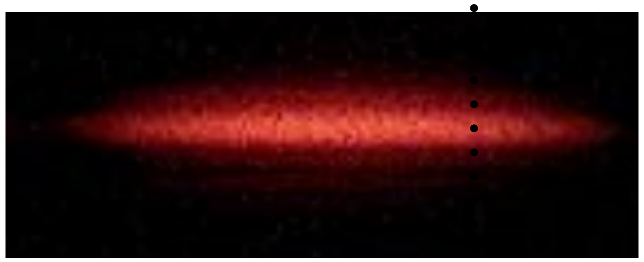


Young’s Double-slit experiment

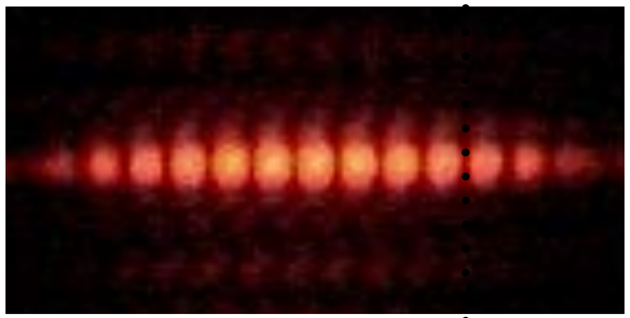
T. Young

- Consider a spot which is **dark** in the two slit pattern.

One slit

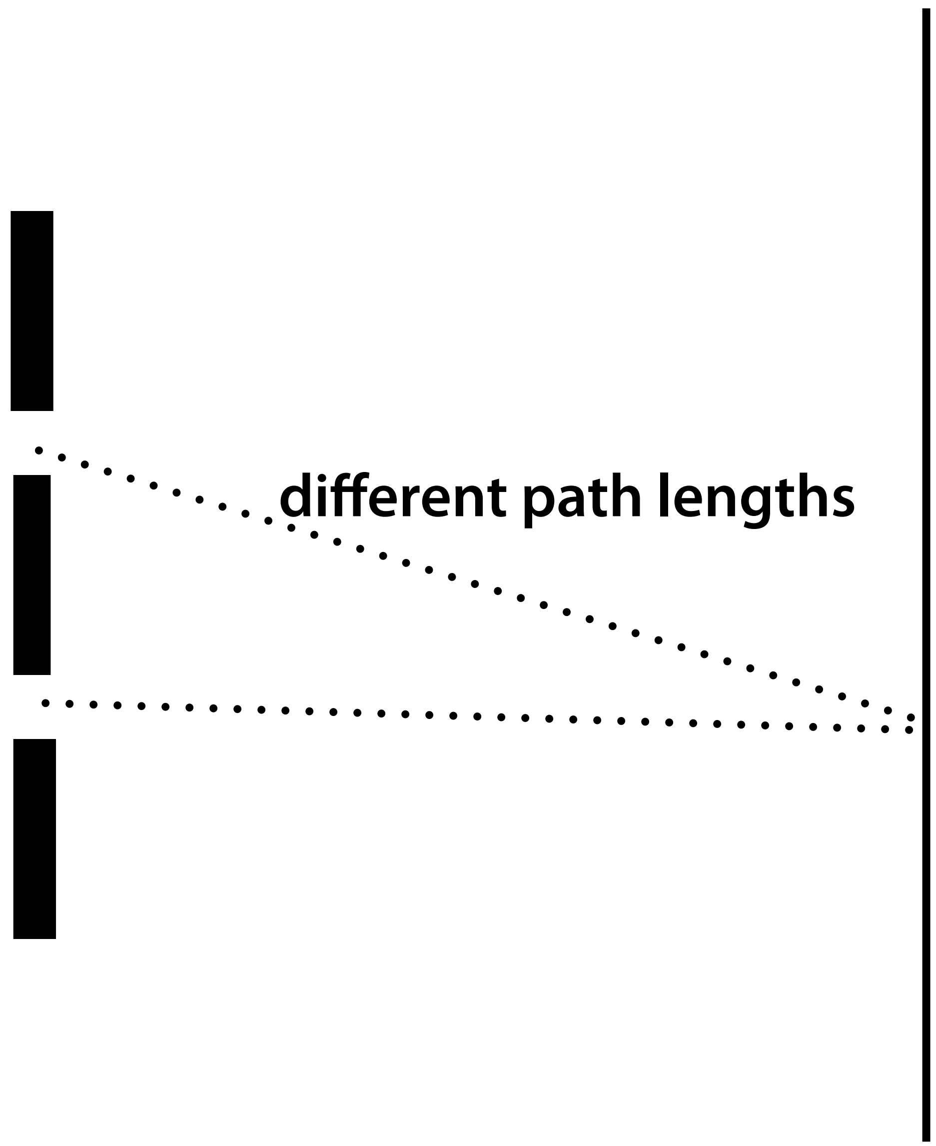


Two slits

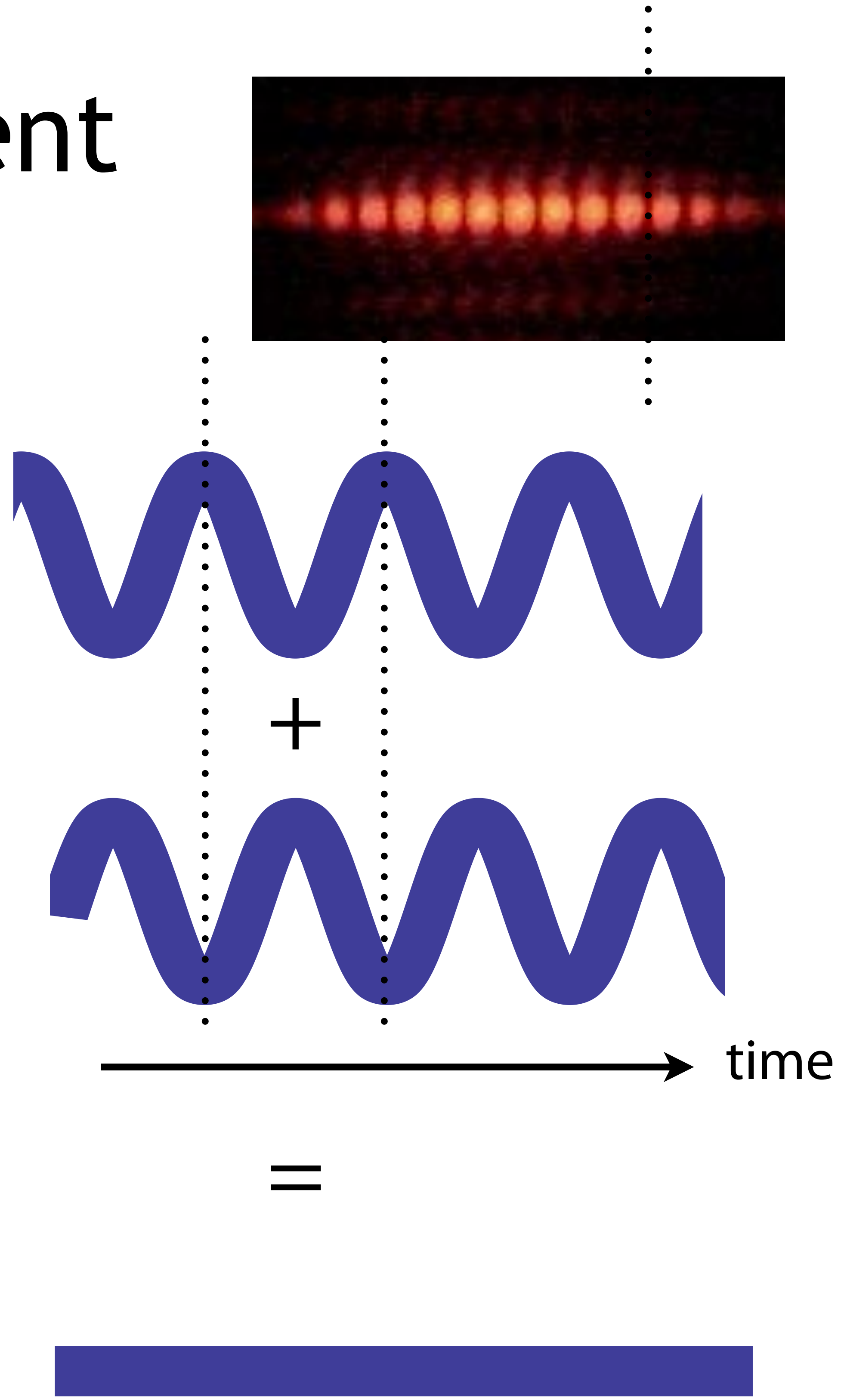


- Note that opening the 2nd slit (providing extra light) has made this point **darker**!

Young's Double-slit experiment

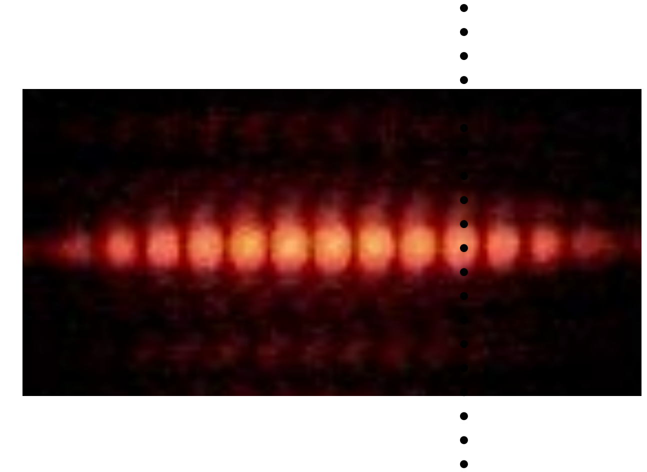


"in-antiphase"

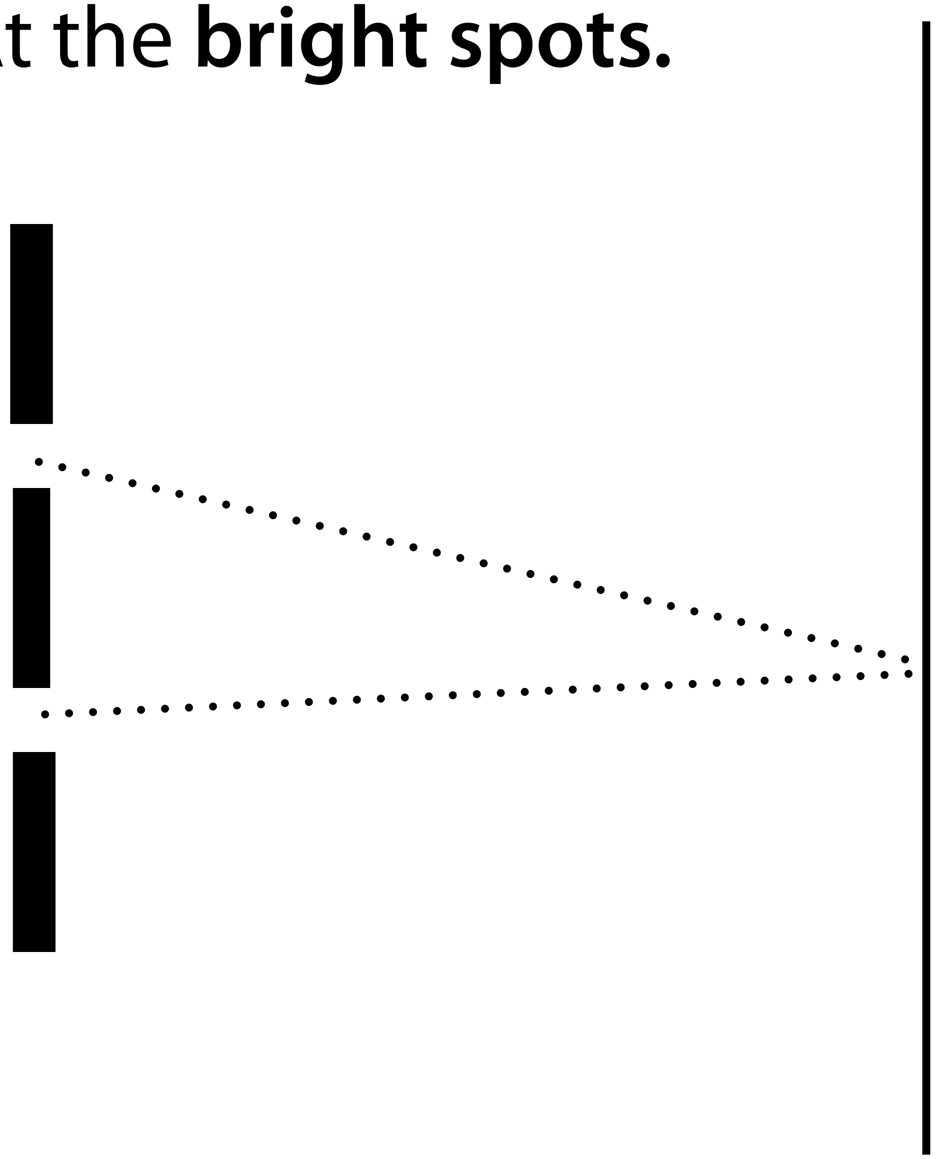


- When the light from the **top slit** has a **peak**, the light from the **bottom slit** has a **trough**.
- The waves **cancel out**.
- We call this **destructive interference**.

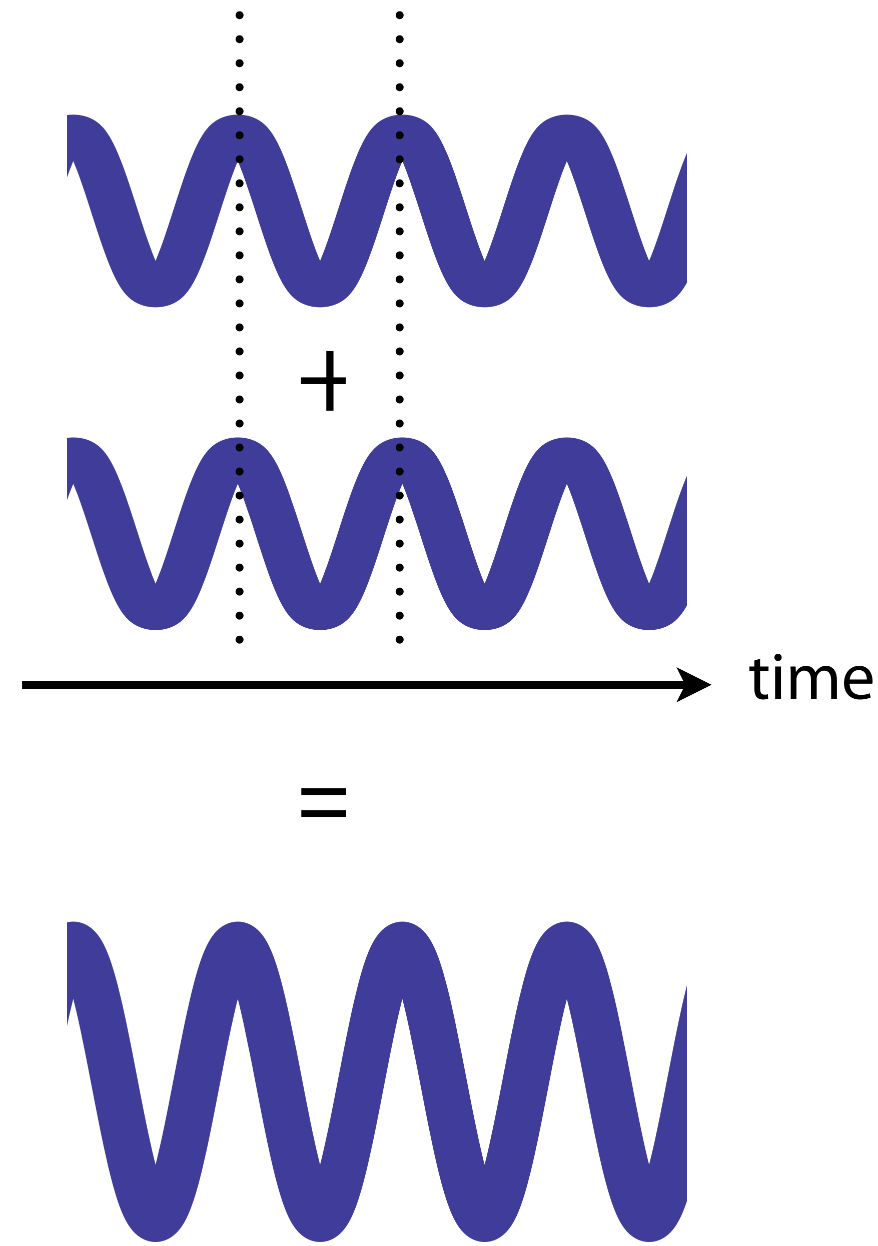
Young's Double-slit experiment



At the **bright spots.**



"in-phase"



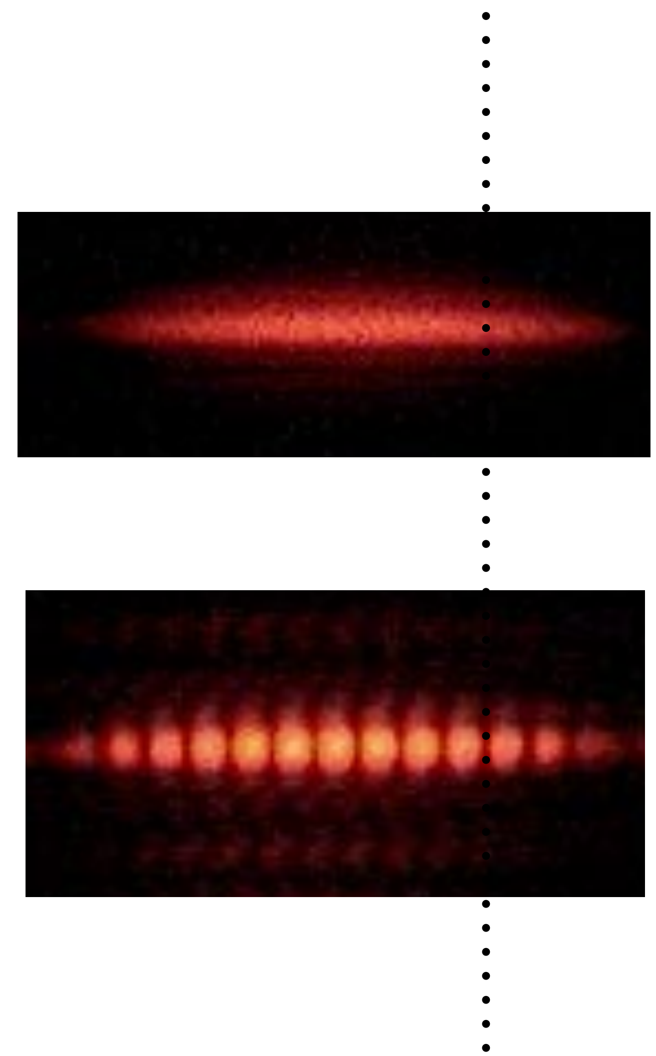
- When the light from the **top slit** has a **peak**, the light from the **bottom slit** has a **peak.**
- The waves **add up**.
- We call this **constructive interference**.

Young’s Double-slit experiment

- Strong evidence against Newton’s particle model.

One slit

Two slits



- The dark spot has to “**know**” about both slits.
- Therefore a **particle picture** is **ruled out**.
- (Since - ***surely*** particles can ***only go through one slit***...)

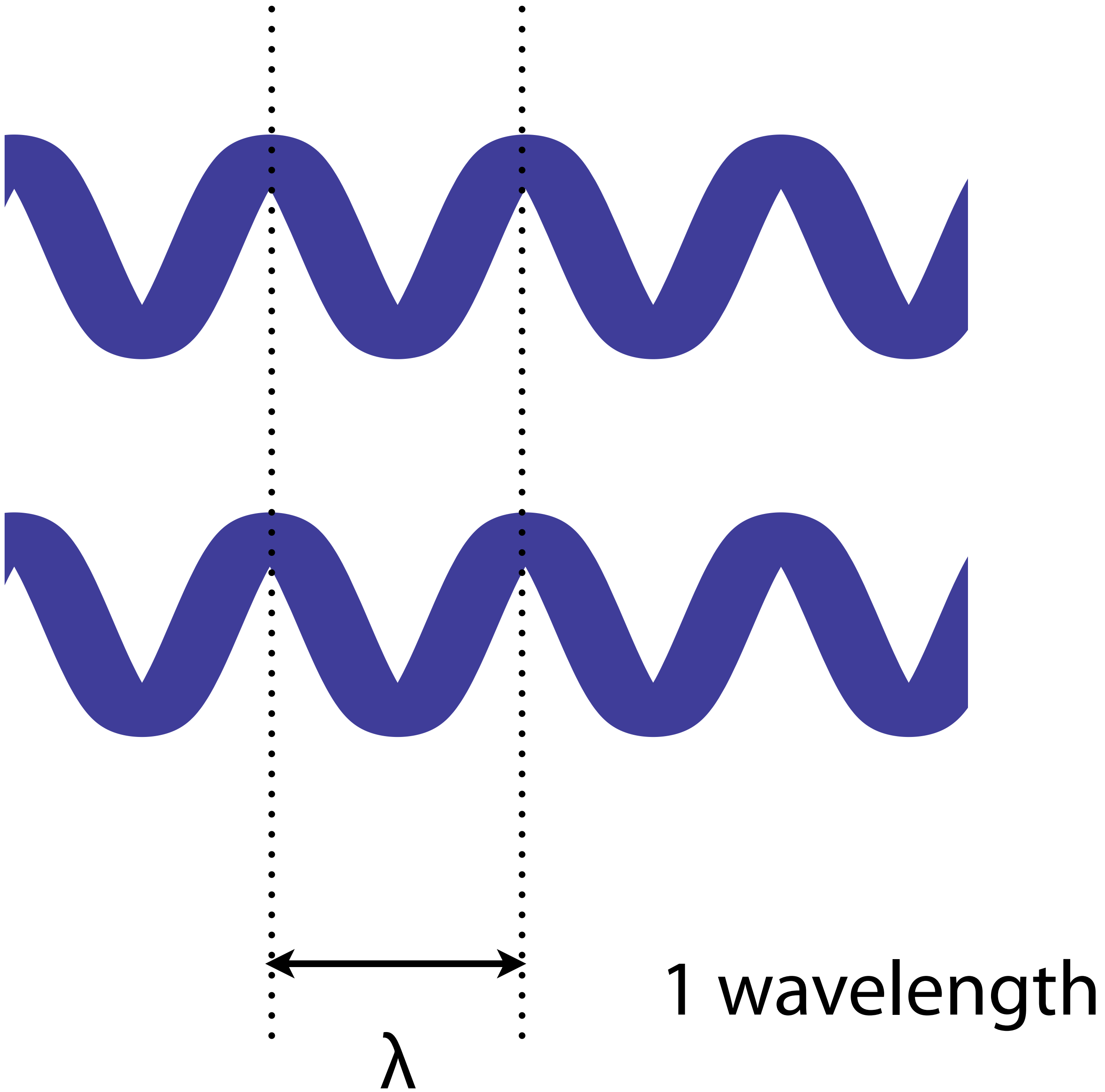
Phase shift

- When a phase difference arises between two waves we say a **phase shift** has occurred.

Phase shift

- Examples

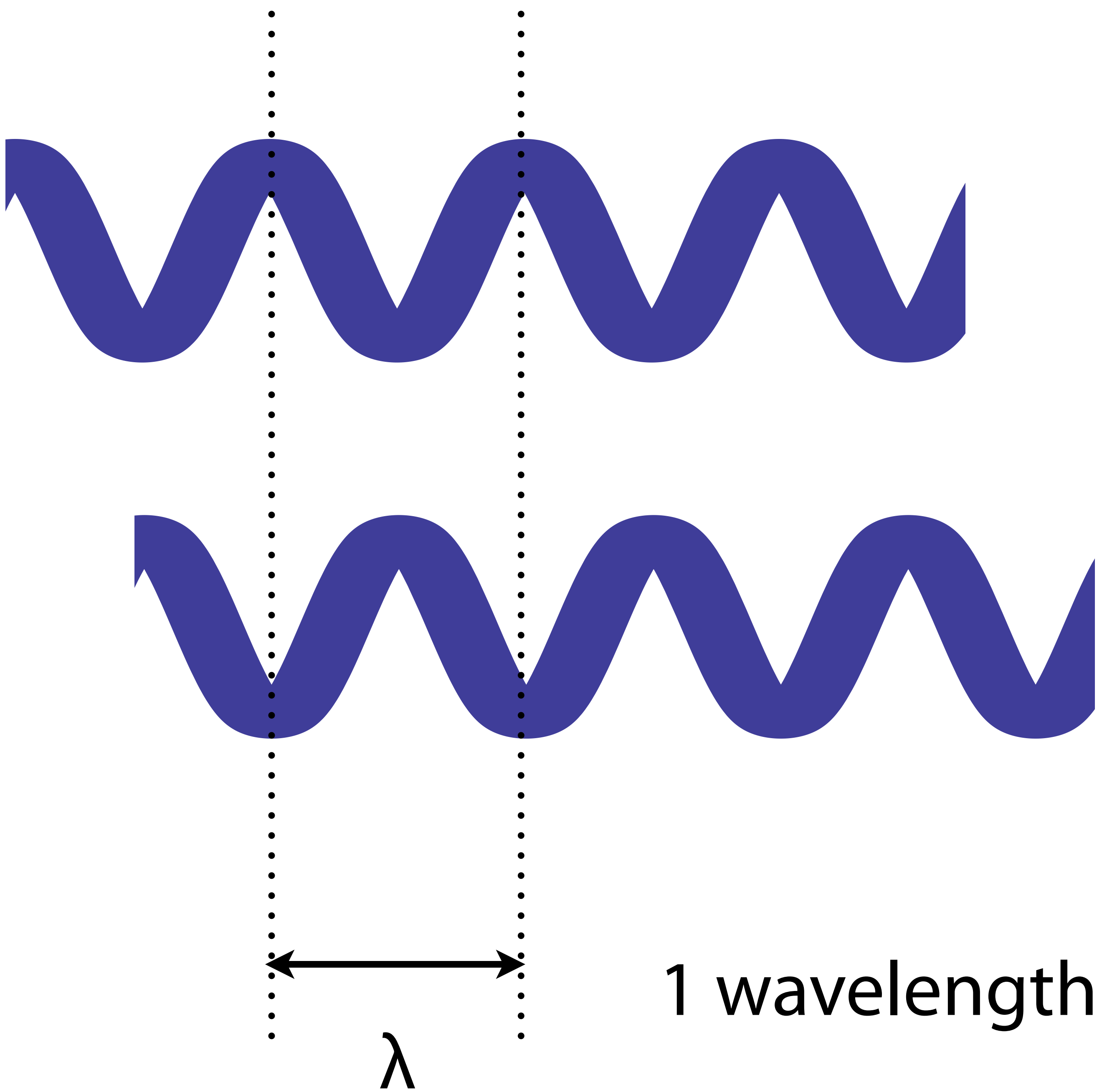
1/2 wavelength phase shift



Phase shift

- Examples

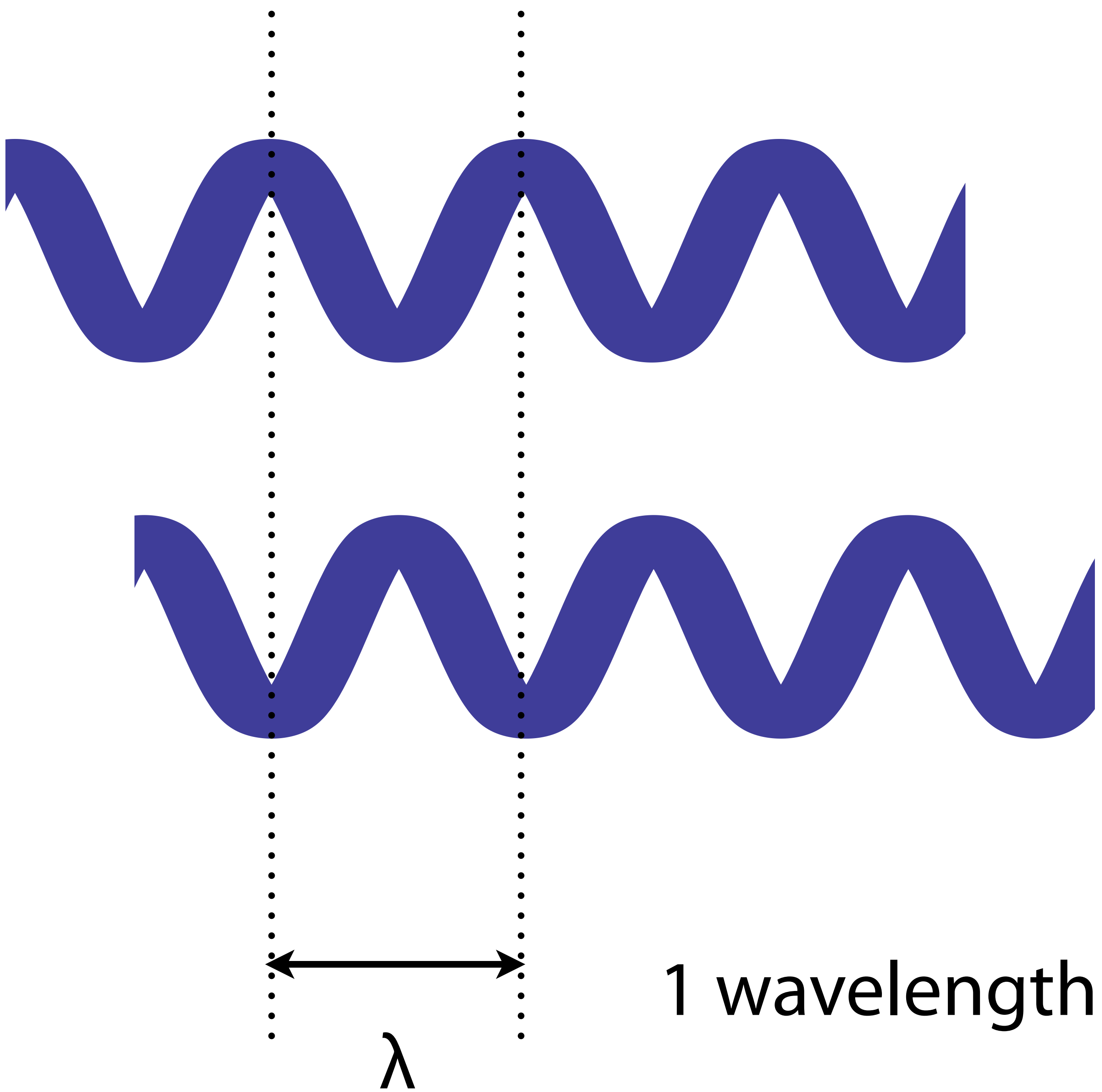
1/2 wavelength phase shift



Phase shift

- Examples

1/2 wavelength phase shift

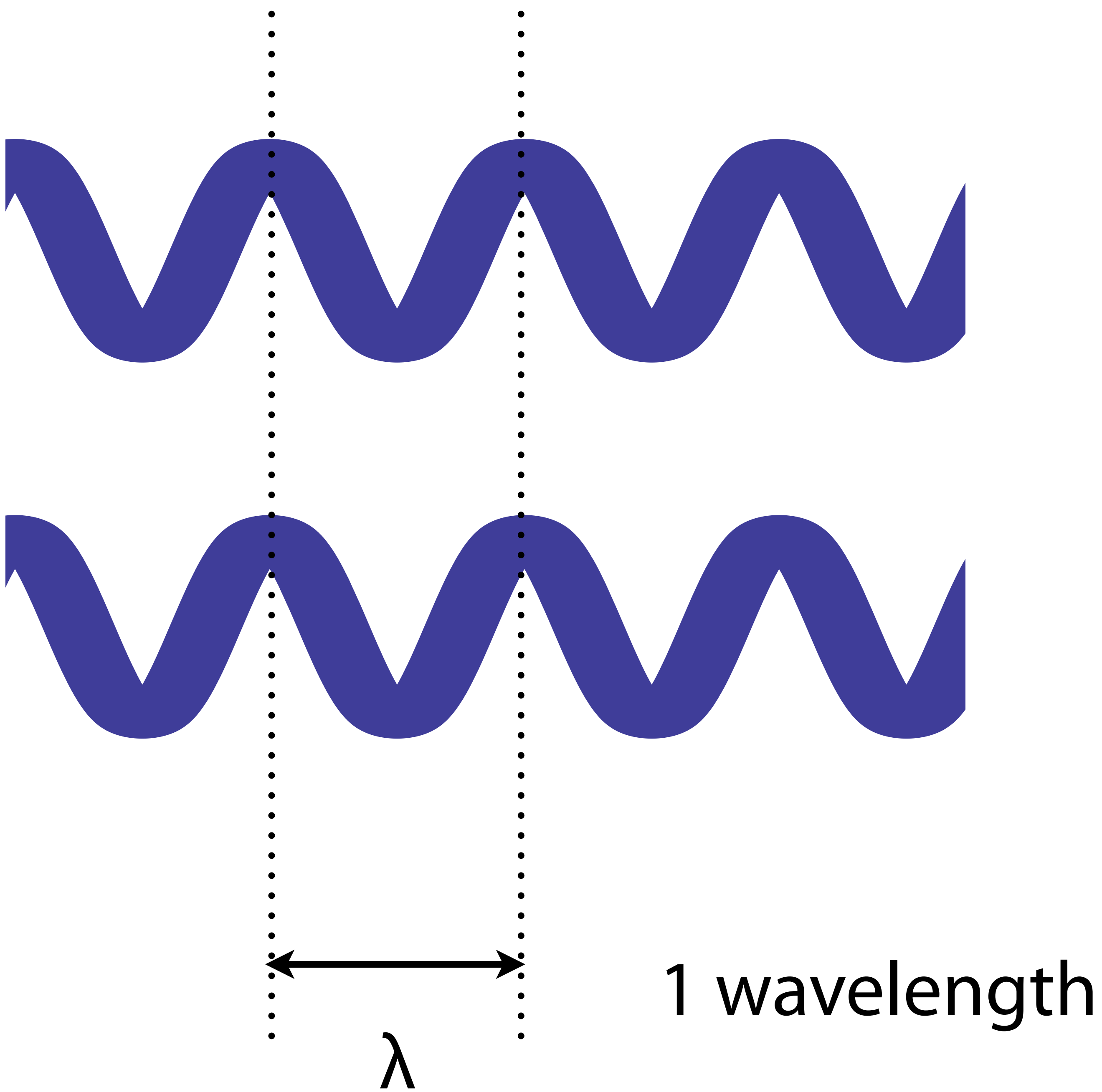


The waves are now **in antiphase** and will **destructively** interfere.

Phase shift

- Examples

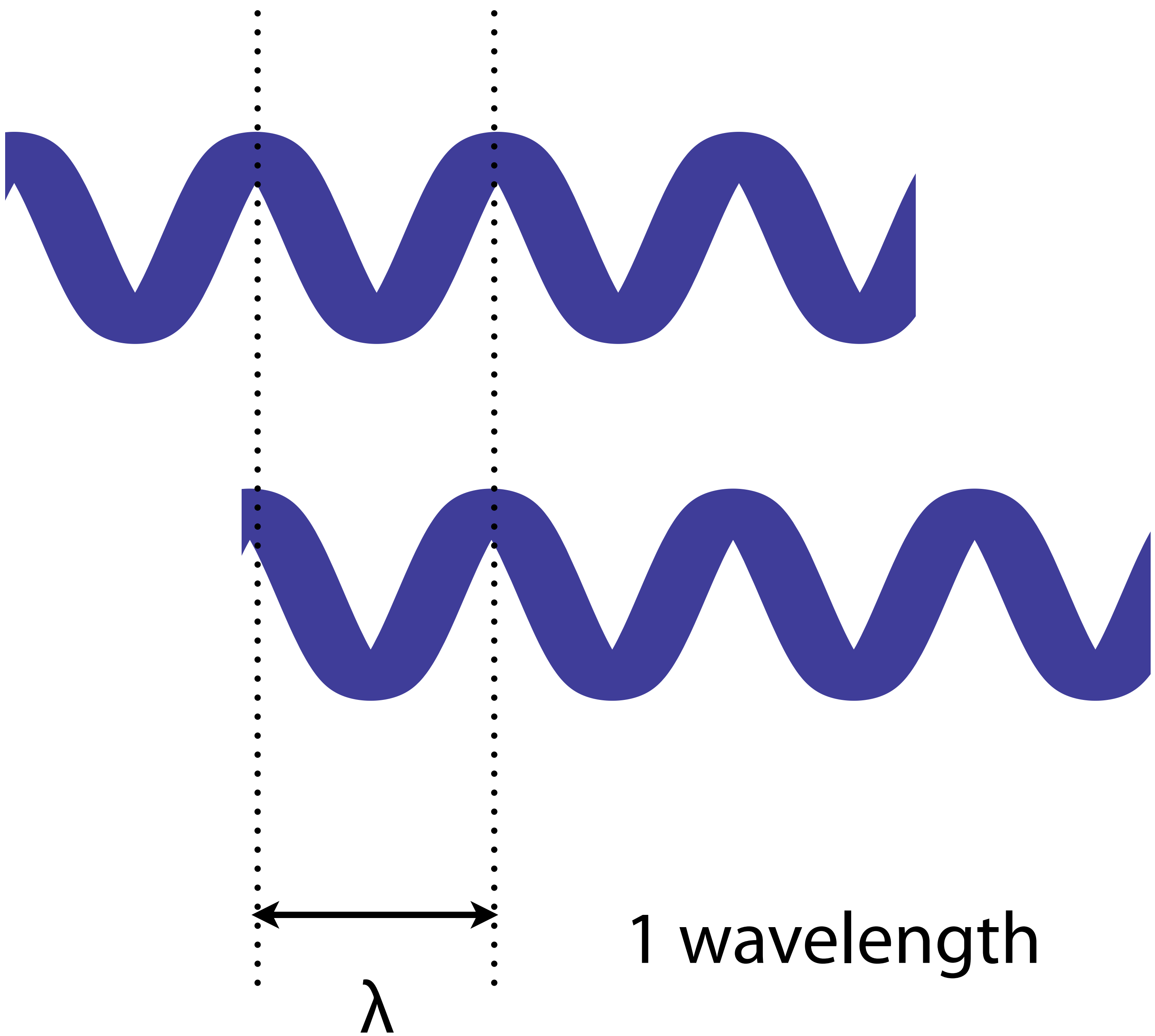
Whole wavelength phase shift



Phase shift

- Examples

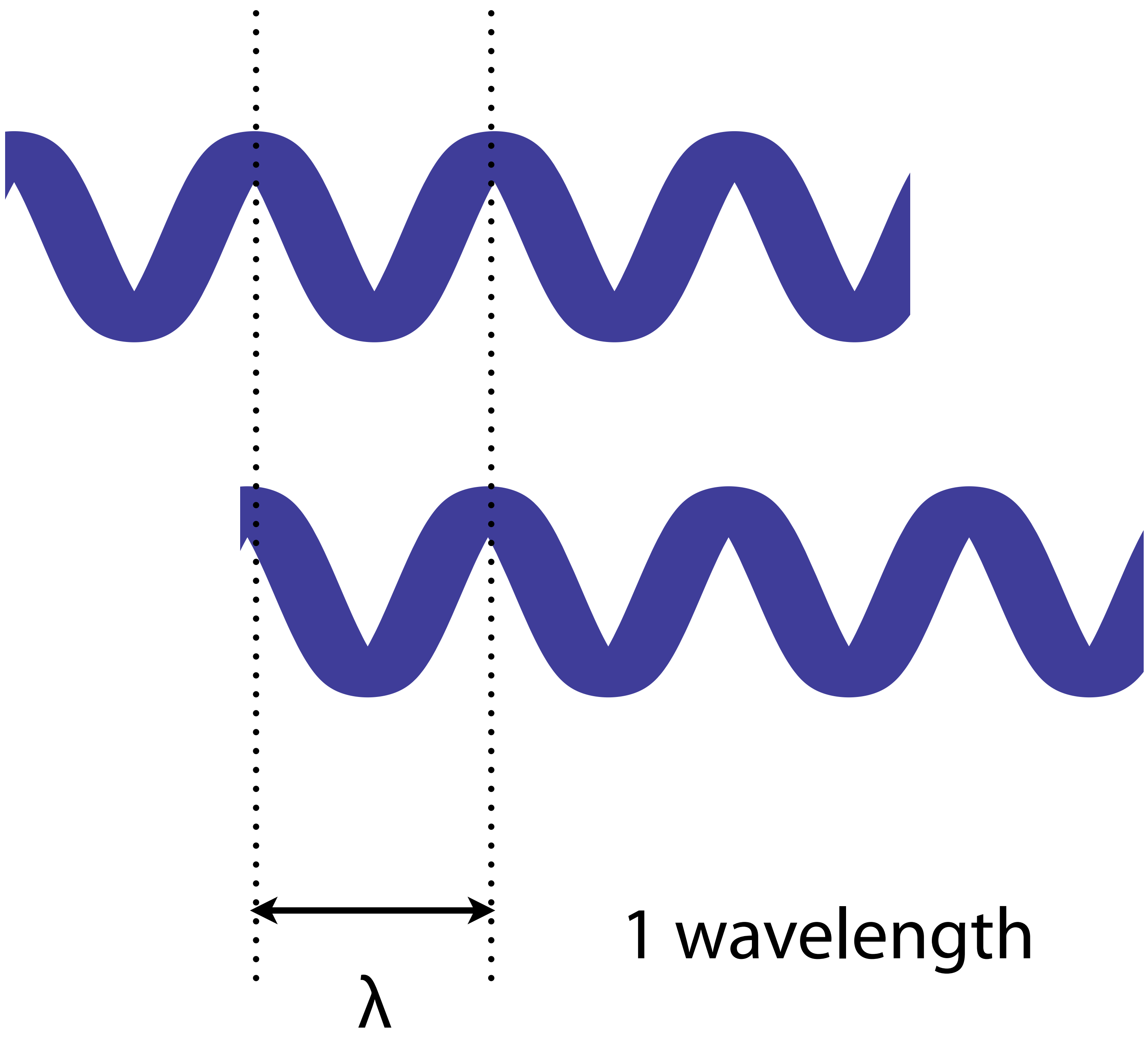
Whole wavelength phase shift



Phase shift

- Examples

Whole wavelength phase shift

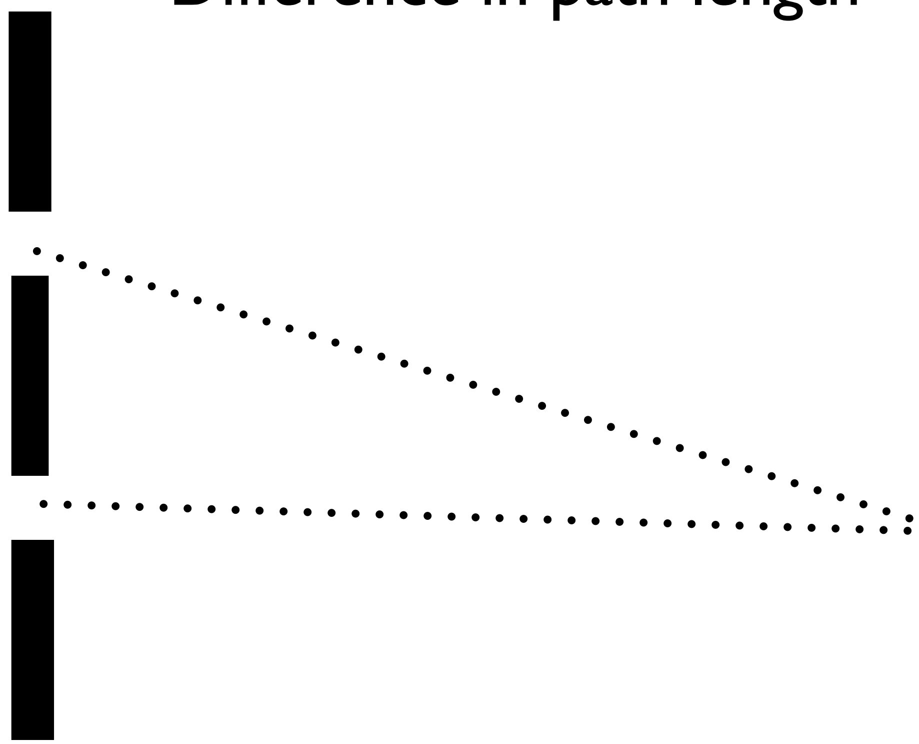


The waves are now **in phase** and will **constructively** interfere.

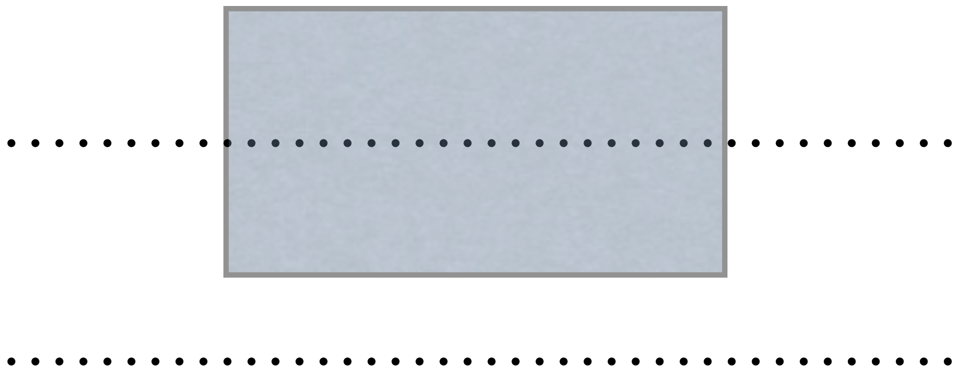
Phase shift

- In optics phase shifts can be caused by different things:

Difference in path length



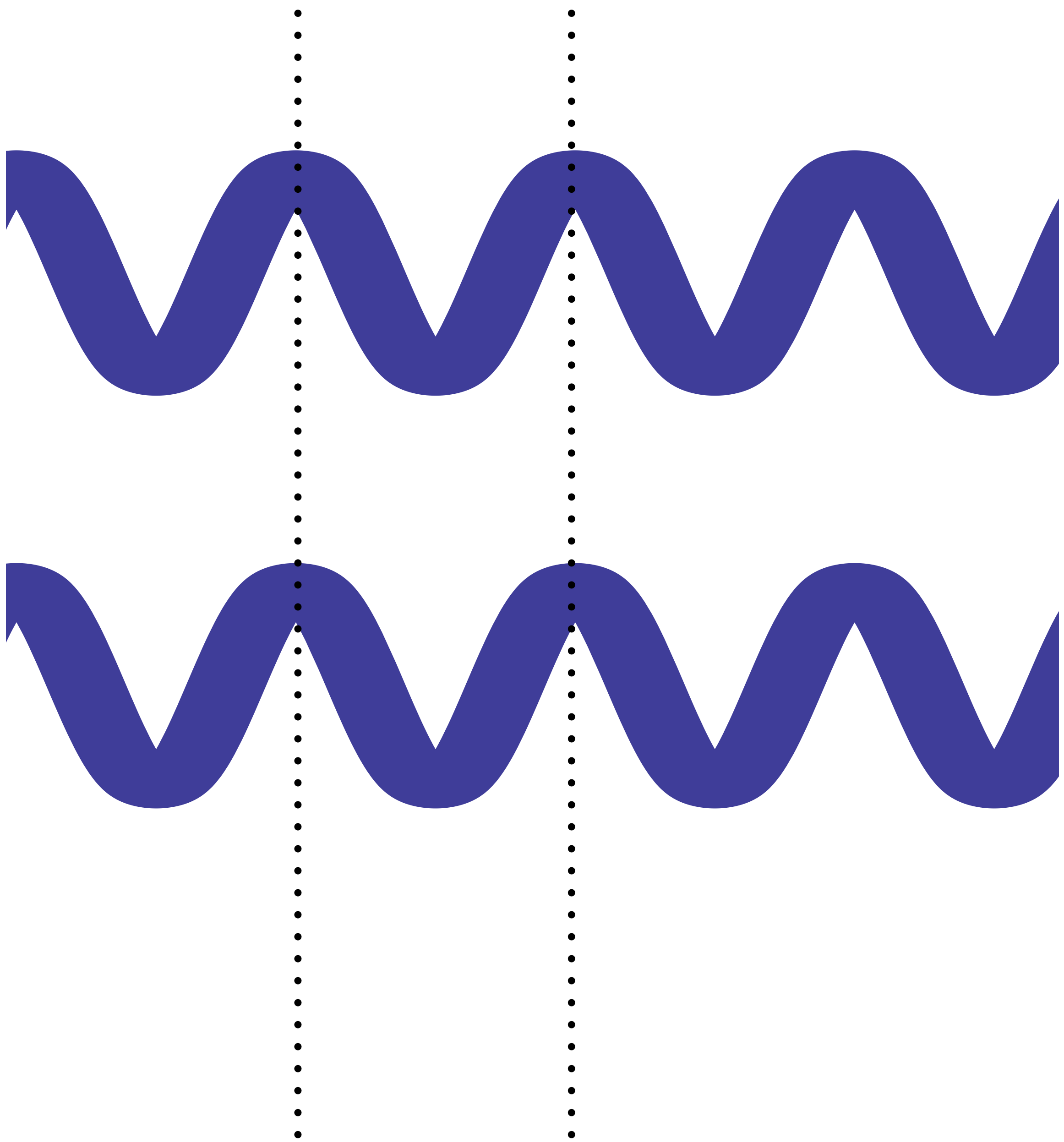
Passing through a crystal



- NB A **phase shift** is a relative property, one beam shifts phase relative to the other.

Quiz

- If I have two beams of light which are initially **in phase** and I then give the second beam a 1/4 wavelength phase shift, will the beams be:



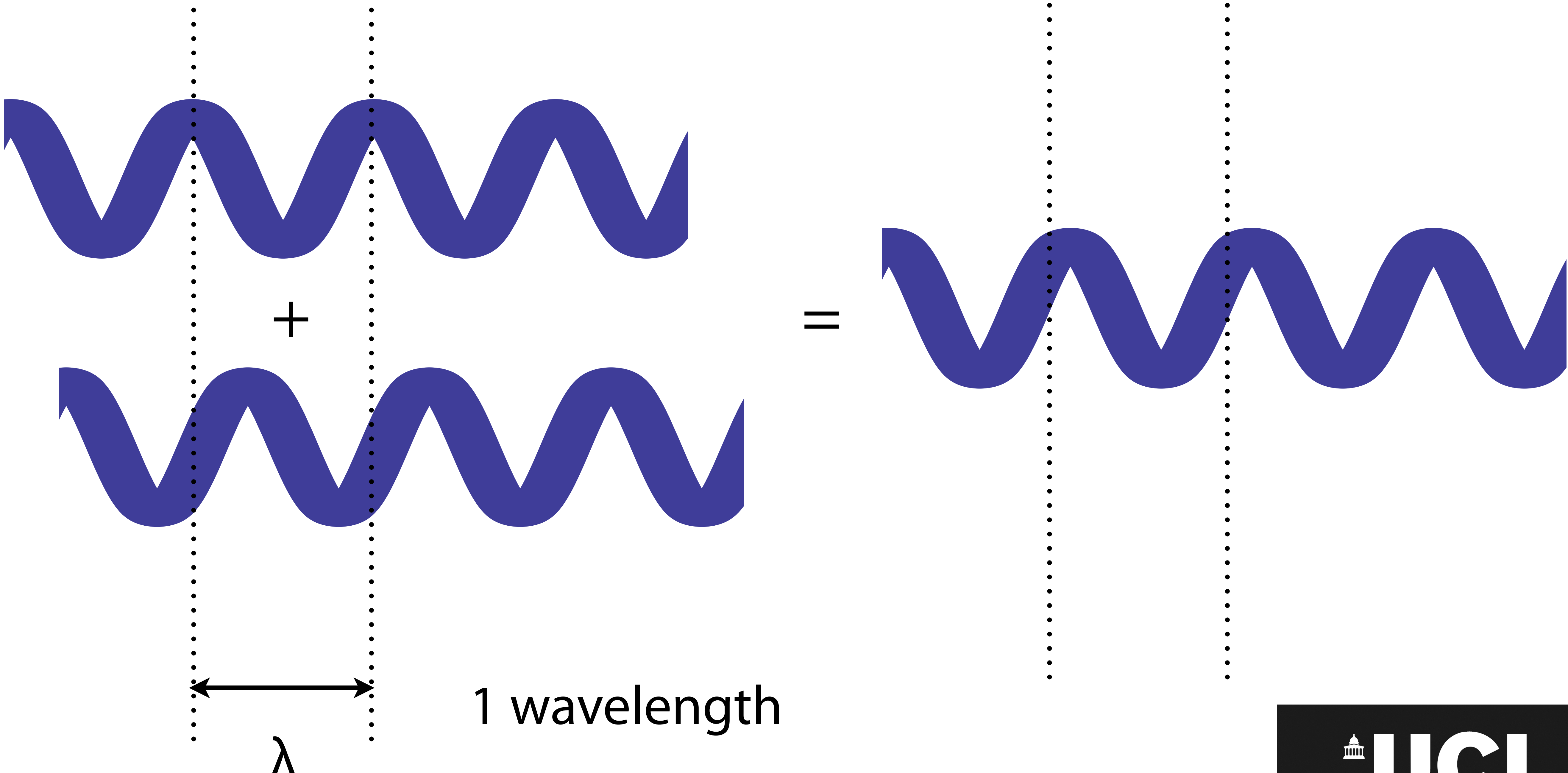
- 1. In phase
- 2. In anti-phase
- 3. Neither in phase or anti-phase.

Phase shift

- Examples

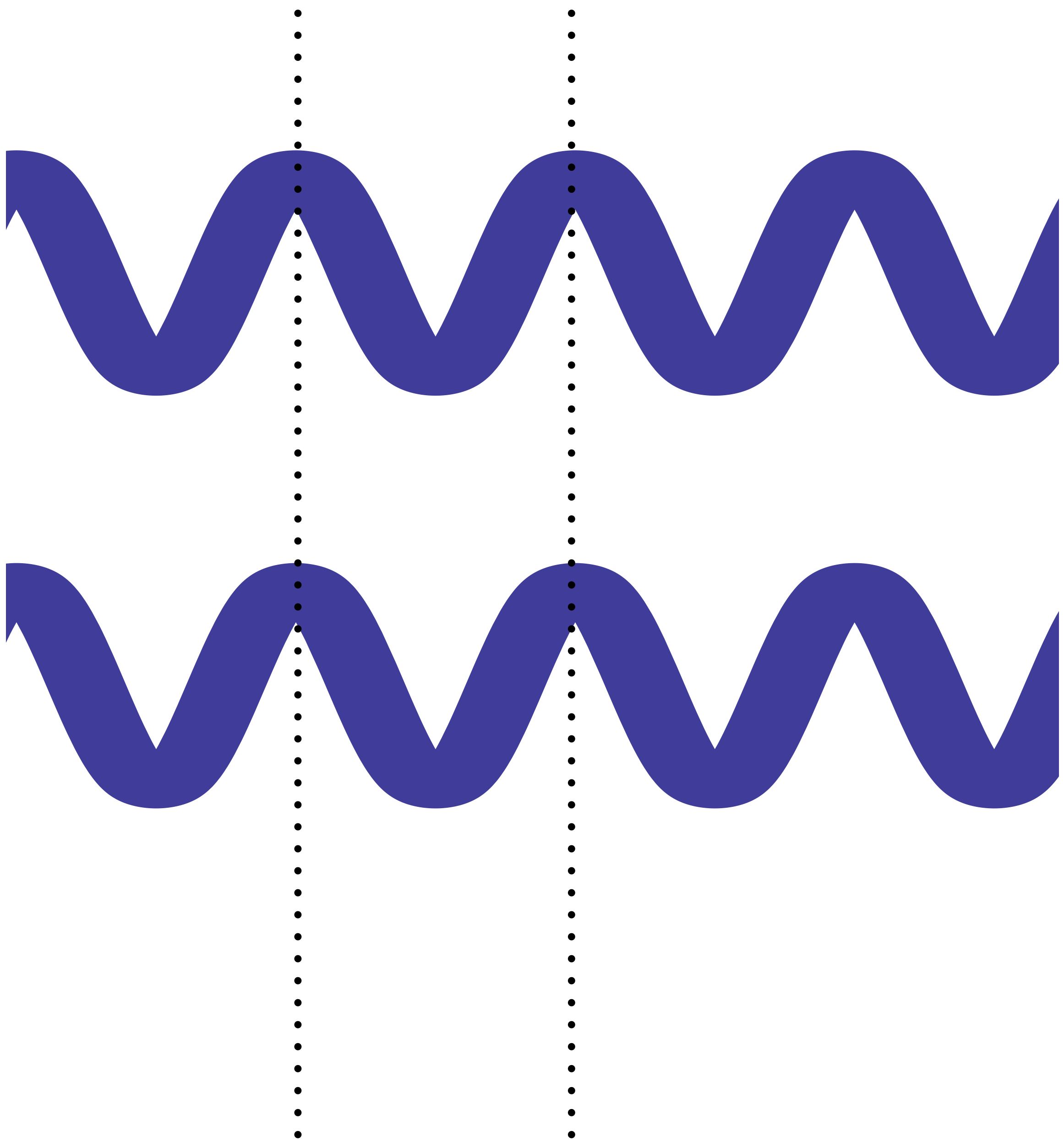
1/4 wavelength phase shift

The waves are **neither** in phase or in antiphase but **half-way in between**



Quiz

- If I have two beams of light which are initially **in phase** and I then give the second beam **a 1/4 wavelength** phase and then give it **another 1/4 wavelength phase-shift**, will the beams be:



- 1. In phase
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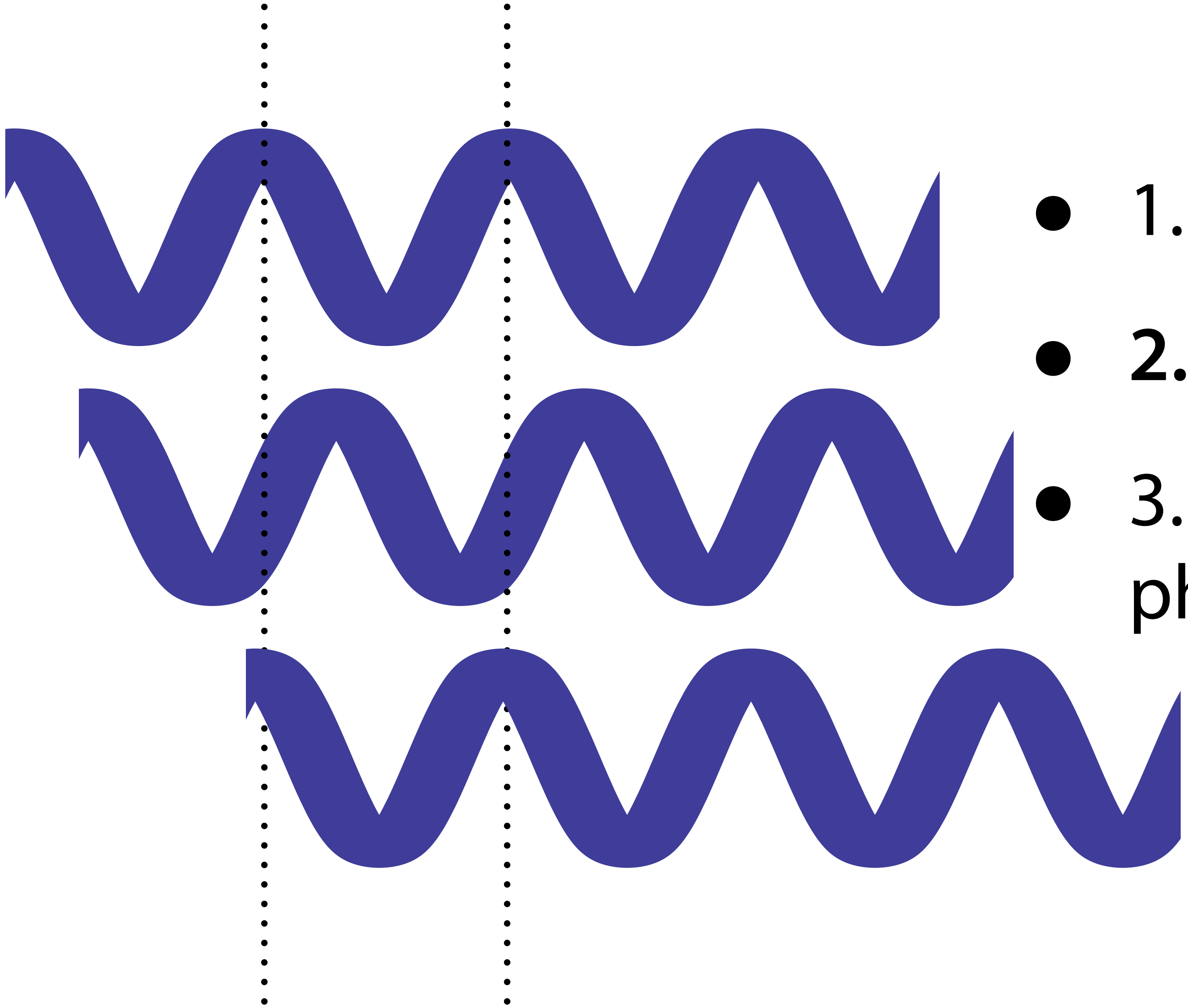
- 3. Neither in phase or anti-phase.

Quiz

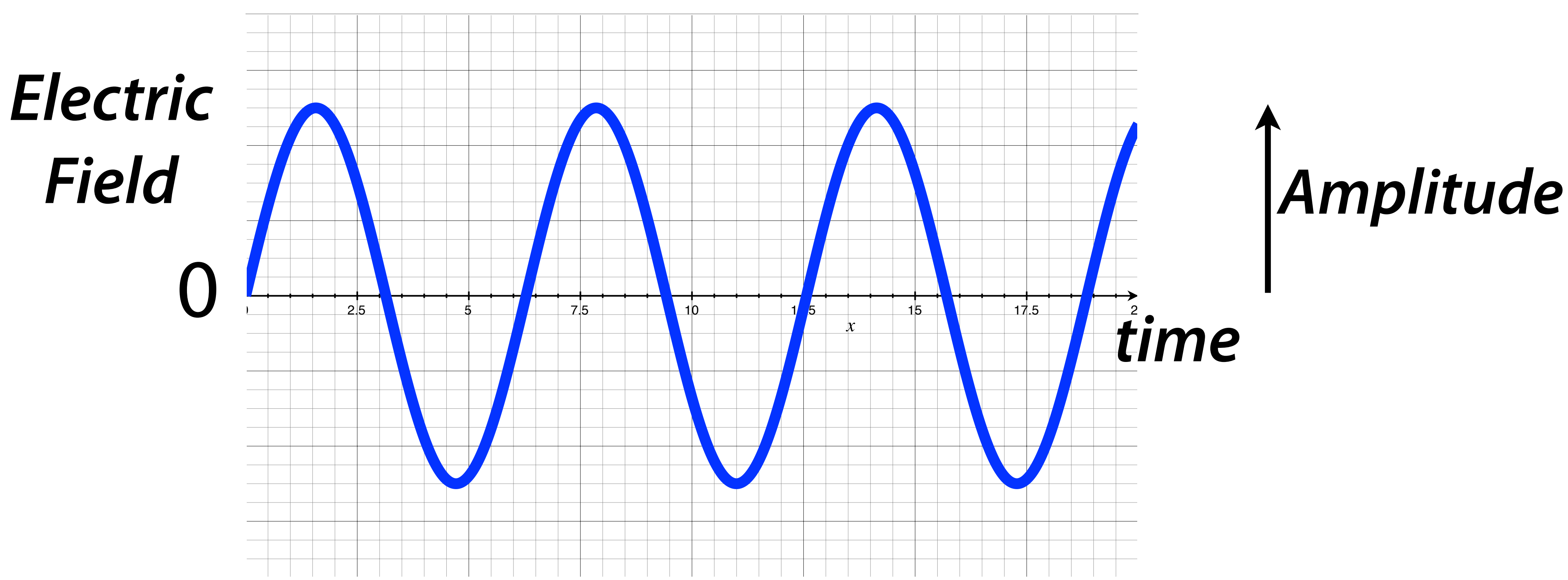
- If I have two beams of light which are initially **in phase** and I then give the second beam **a 1/4 wavelength** phase and then give it **another 1/4 wavelength phase-shift**, will the beams be:



- 1. In phase
- **2. In anti-phase**
- 3. Neither in phase or anti-phase.

Aside: Intensity vs Amplitude

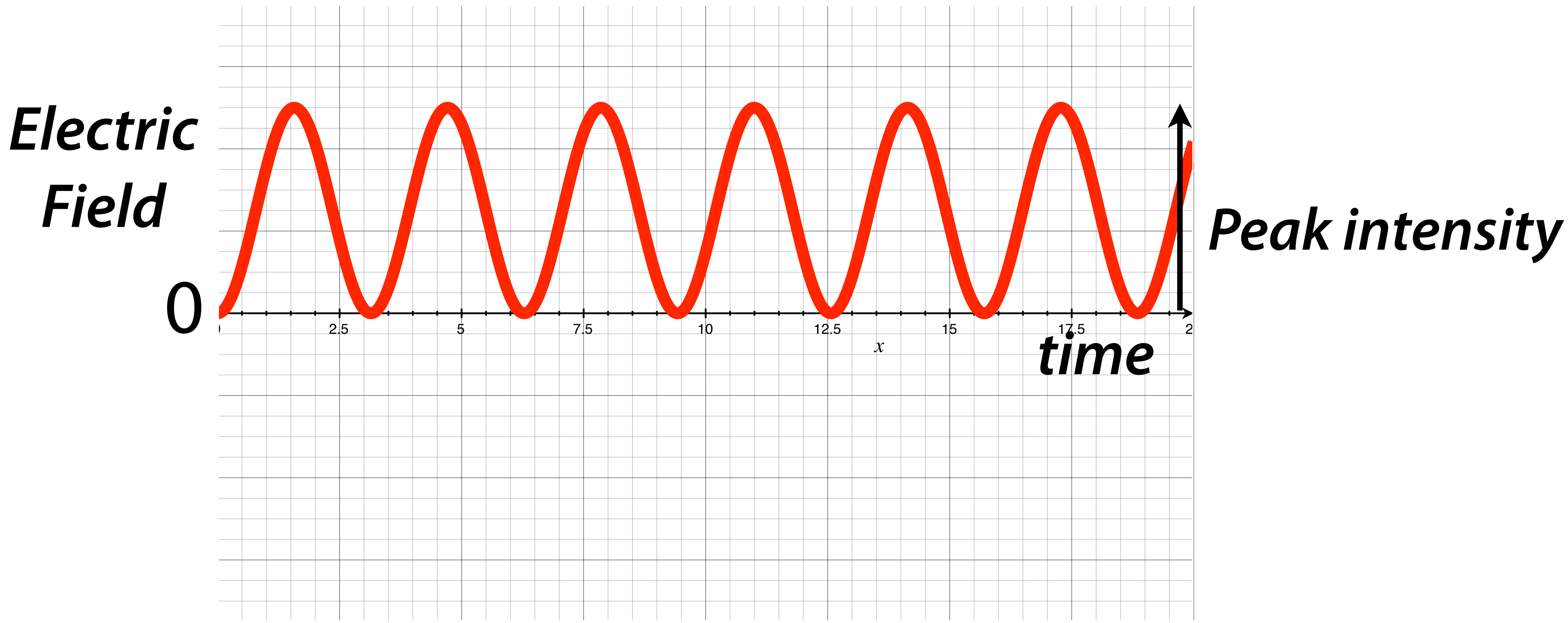
- ***(Classical theory of) light***
  - A wave in electric and magnetic fields.



- NB Electric Field is **positive** and **negative**
- The **height** of the wave from 0 is called the **amplitude**.

Aside: Intensity vs Amplitude

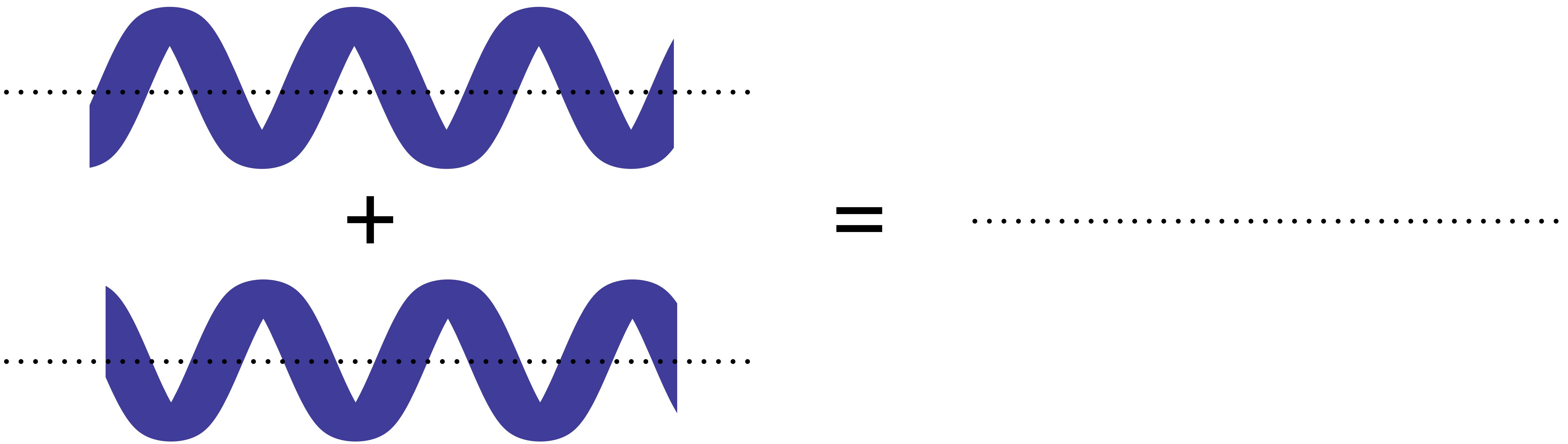
- ***(Classical theory of) light***
  - Intensity is the amplitude squared.



- It is always **never negative** than **zero**.
- The intensity (power) of light we see is the average over time.

Aside: Intensity vs Amplitude

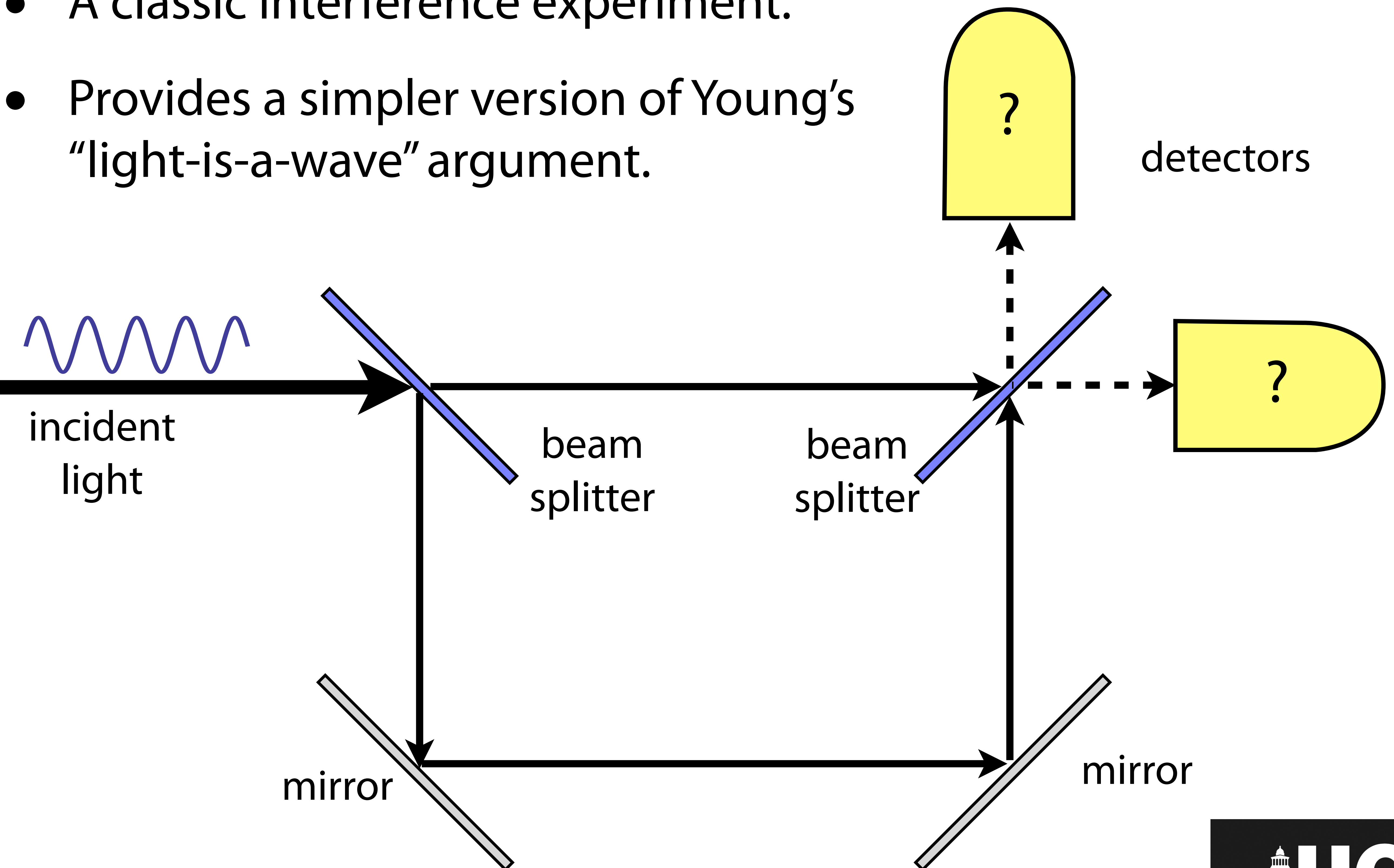
- ***(Classical theory of) light***
  - Interference happens on the level of **amplitudes**.



  - The brightness we observe is the resulting **intensity**.

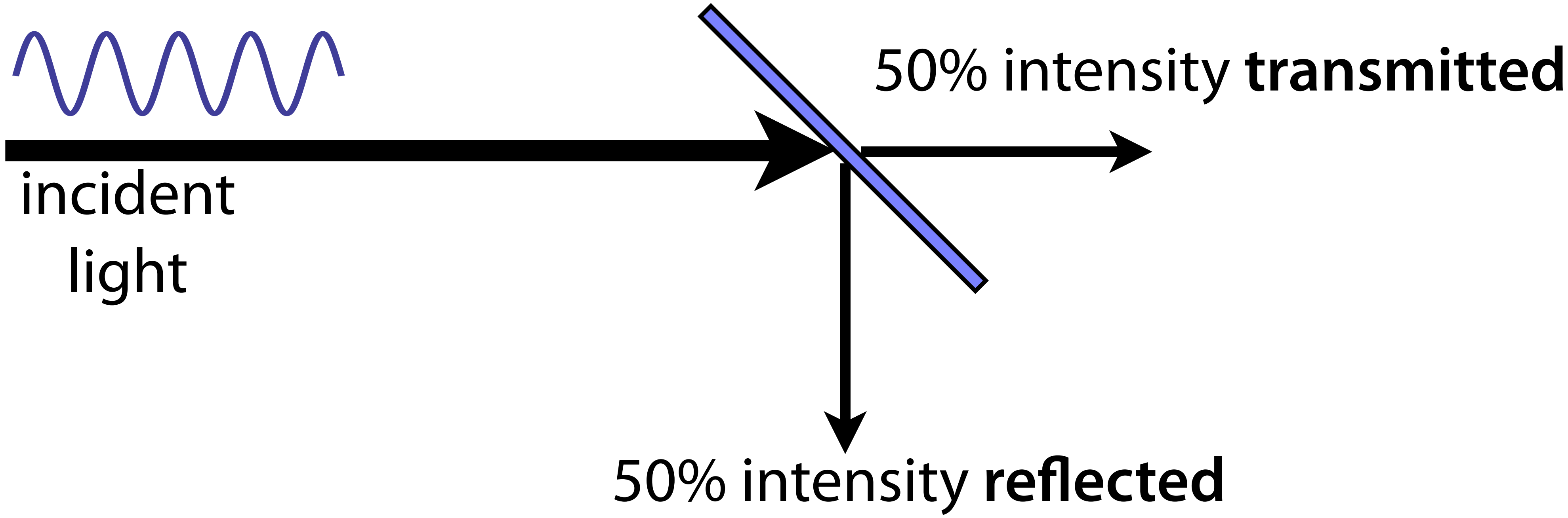
The Mach-Zehnder interferometer

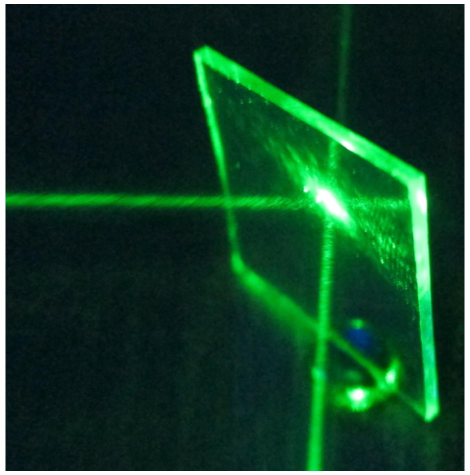
- A classic interference experiment.
- Provides a simpler version of Young's "light-is-a-wave" argument.



Mach-Zehnder Interferometer

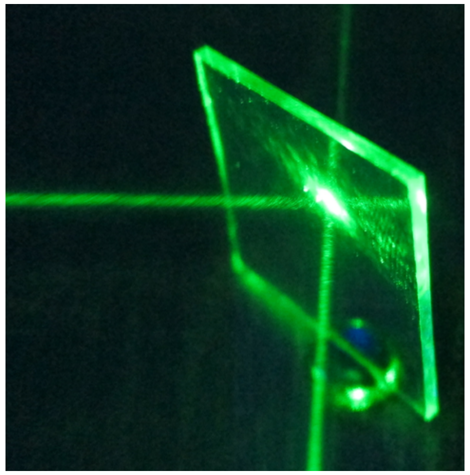
- **Beam splitter -** A "semi-silvered mirror"
  - Most reflecting surfaces reflect **and transmit.**
  - A **beam-splitter** is specially tuned **mirror** which transmits 50% of light (**intensity**) and reflects 50% of light (**intensity**).

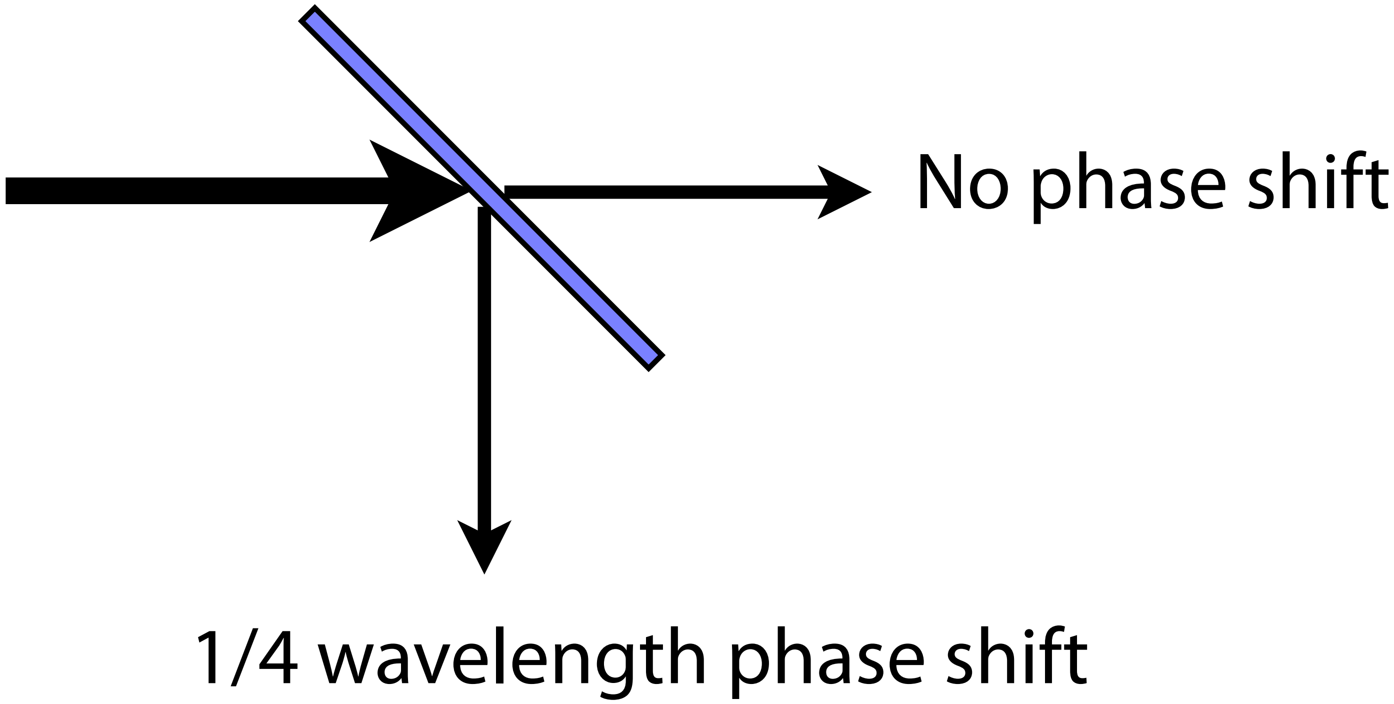




Mach-Zehnder Interferometer

- **Beam splitter** phase shift
  - Reflection on a beam splitter can cause a **phase shift** (necessary for energy conservation).
- **Symmetric beam splitter**
  - Transmission causes **no phase shift**
  - Reflection causes a **1/4 wavelength phase shift**
  - In this course we will **always** consider symmetric beam splitters.





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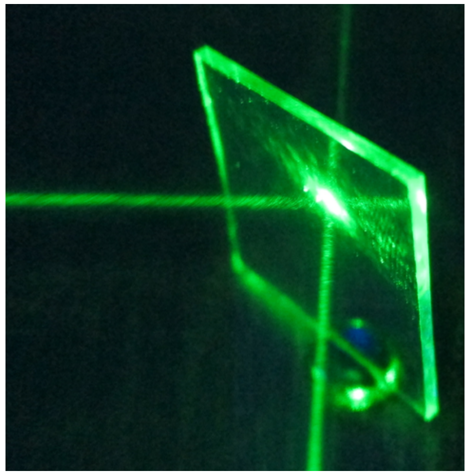
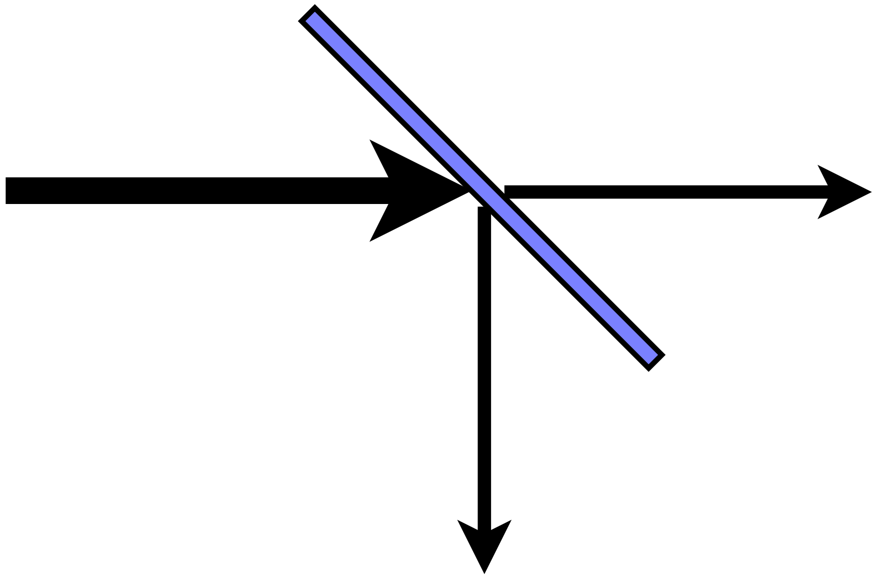




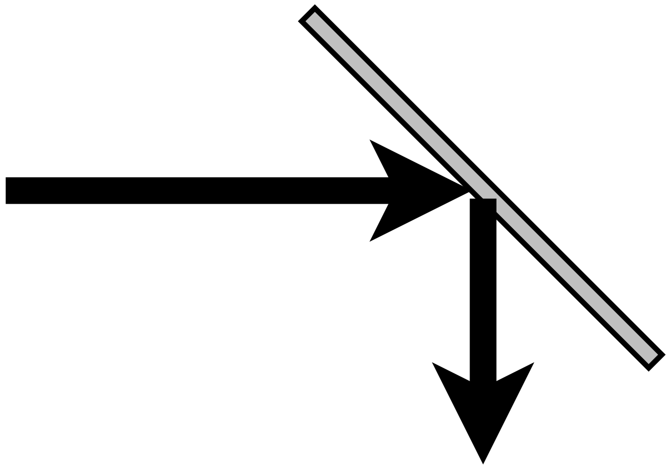
No phase shift

1/4 wavelength phase shift

Mach-Zehnder Interferometer

- *Other components of the M-Z interferometer*
  - **Detector**
    - Indicates the intensity (power) of incident light.
    - Units: Watts = Joules / second

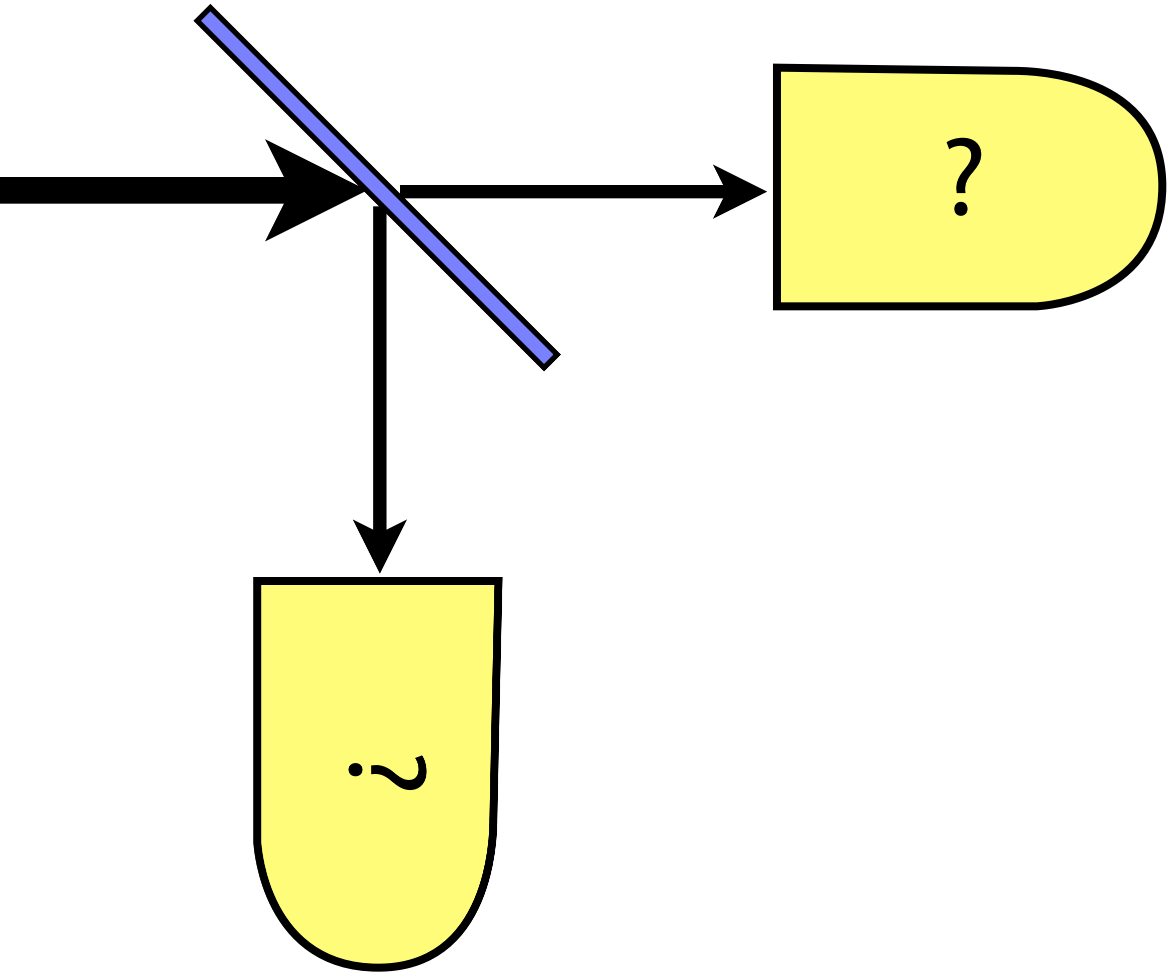
  - **Full Mirror**
    - No transmission
    - **No phase shift** on reflection.



Quiz

- Consider a laser beam with power 10W.

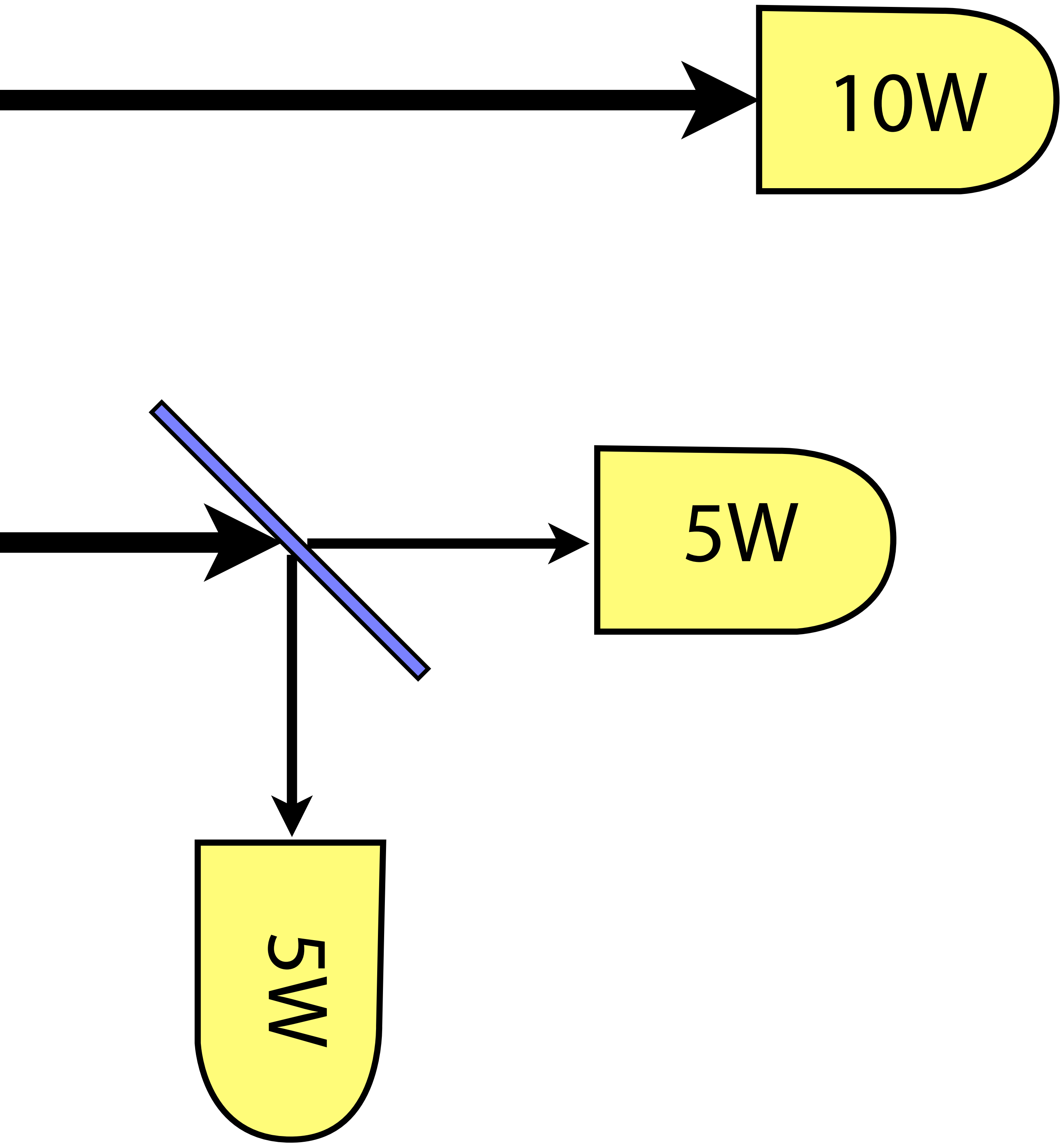
- We split this beam at a beam splitter. What will the detectors say?



- 1. 10W and 10W
- 2. 10W and 0 W
- 3. 5 W and 5 W

Quiz

- Consider a laser beam with power 10W.

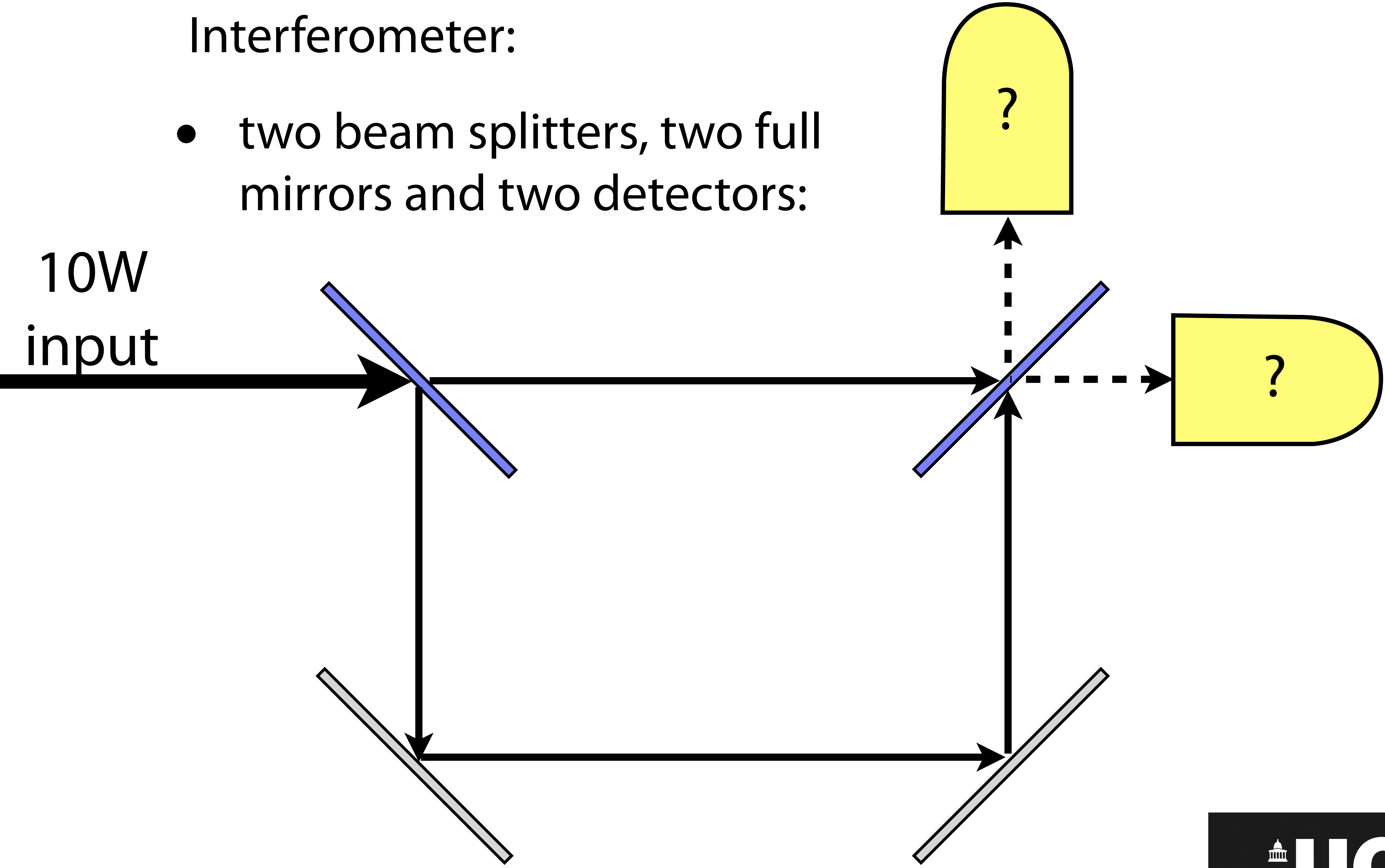


- We split this beam at a beam splitter. What will the detectors say?

- 1. 10W and 10W
- 2. 10W and 0 W
- **3. 5W and 5W**

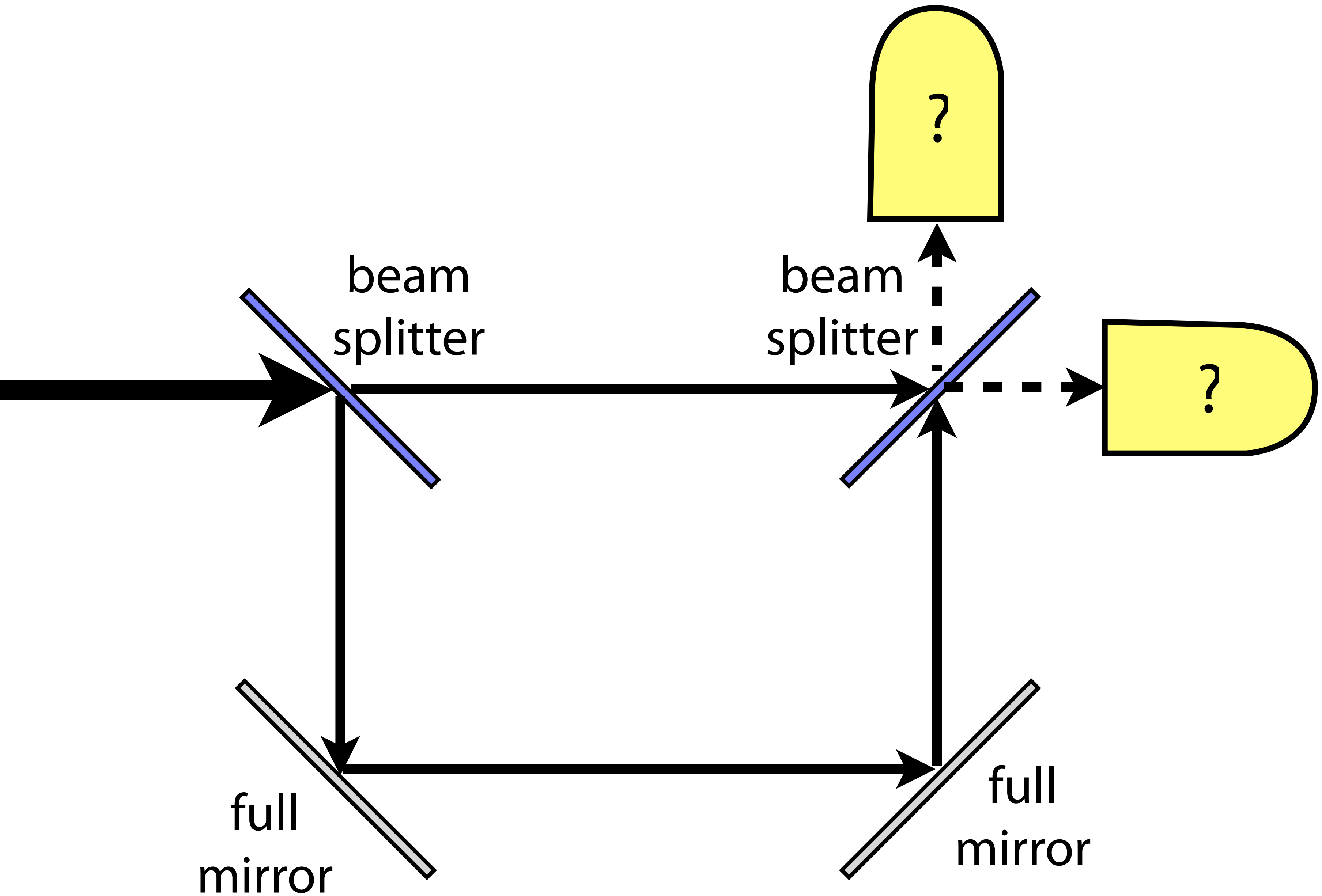
Mach-Zehnder Interferometer

- The **full** Mach-Zehnder Interferometer:
  - two beam splitters, two full mirrors and two detectors:

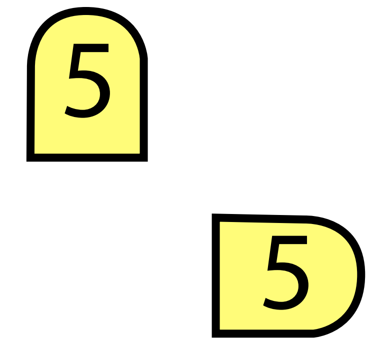


Quiz

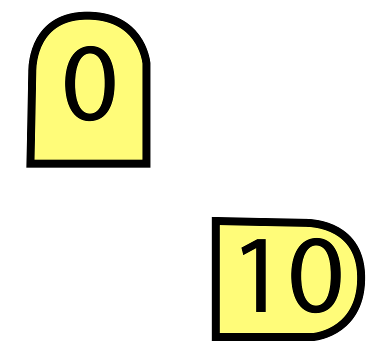
- With 10W input what do you expect to see on the detectors?



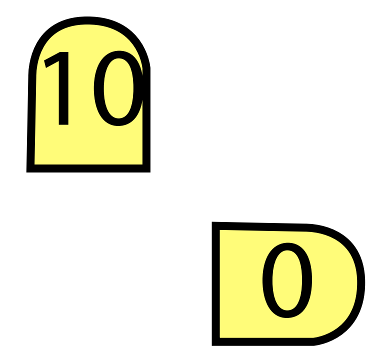
- **1.**



- **2.**

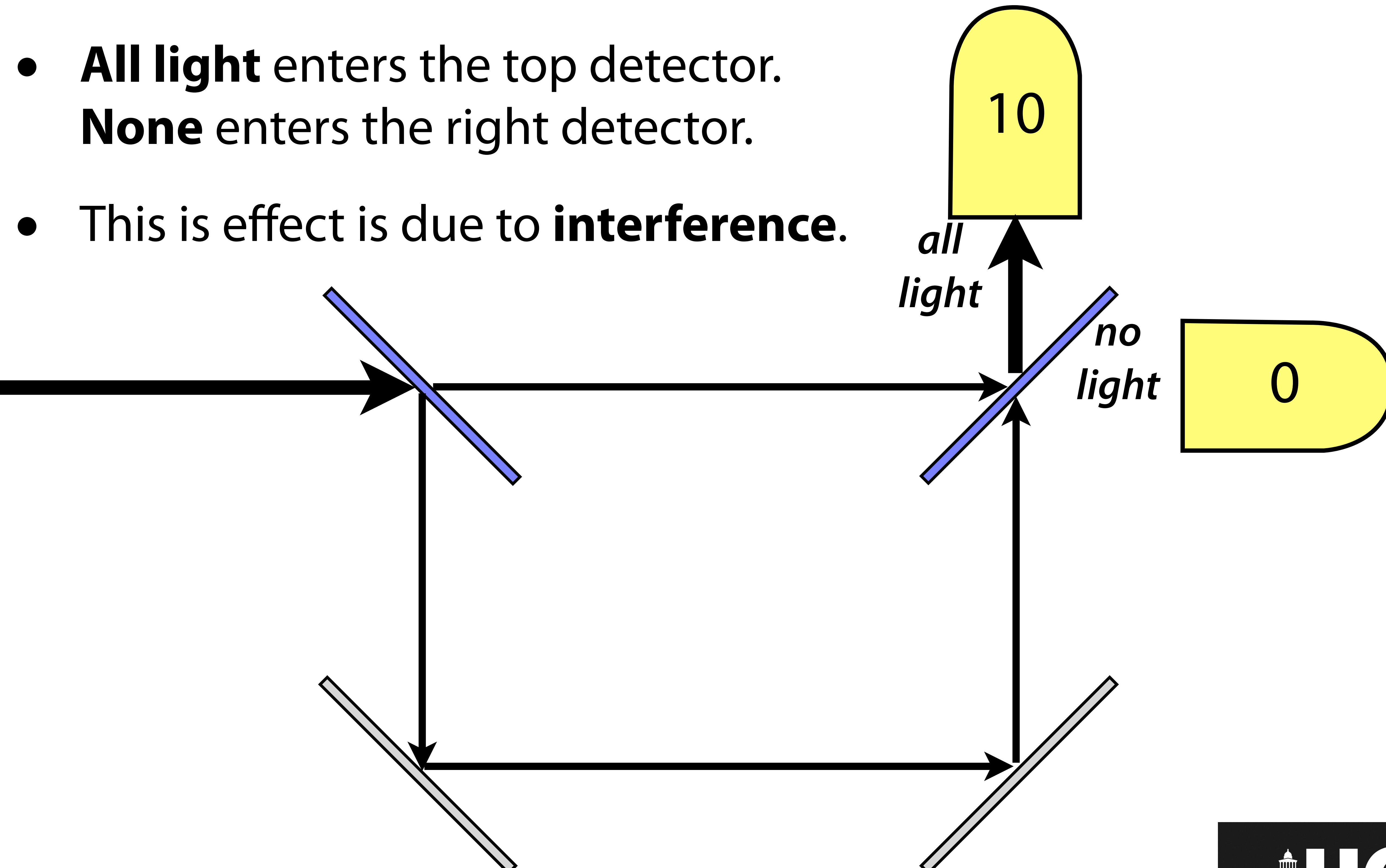


- **3.**



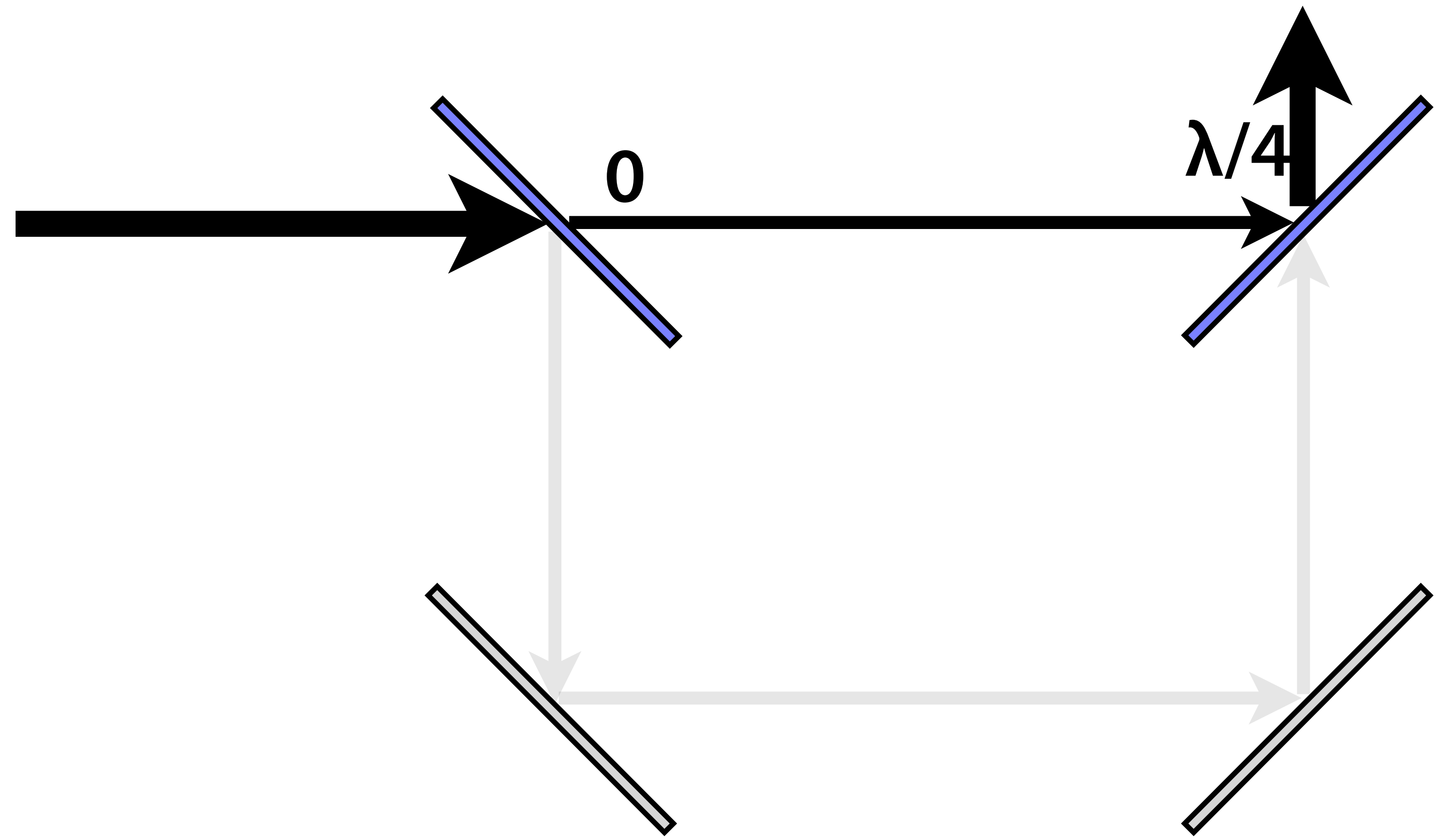
Mach-Zehnder Interferometer

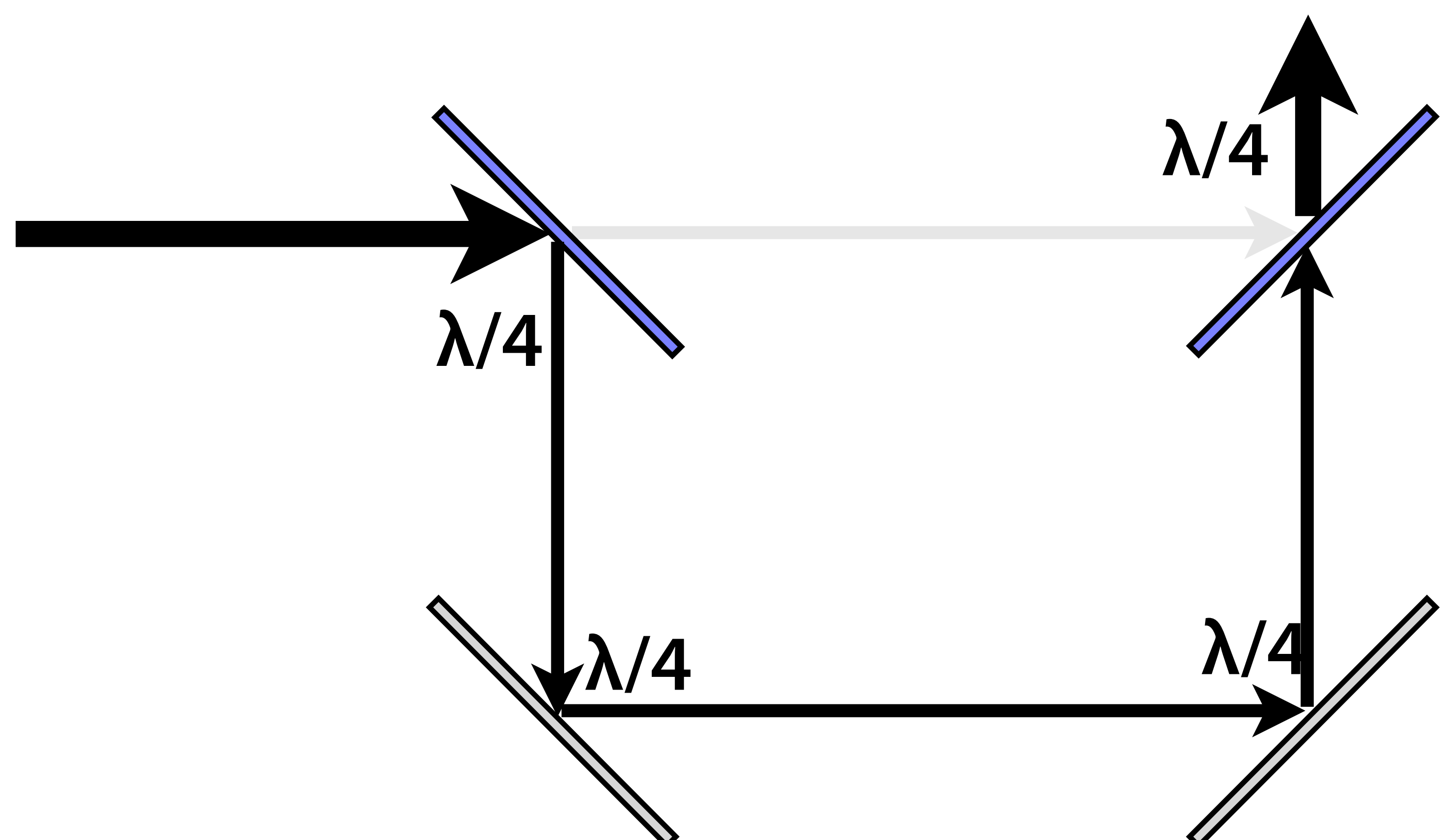
- Option **3** is correct.
- **All light** enters the top detector.
  None enters the right detector.
- This is effect is due to **interference**.



Mach-Zehnder Interferometer

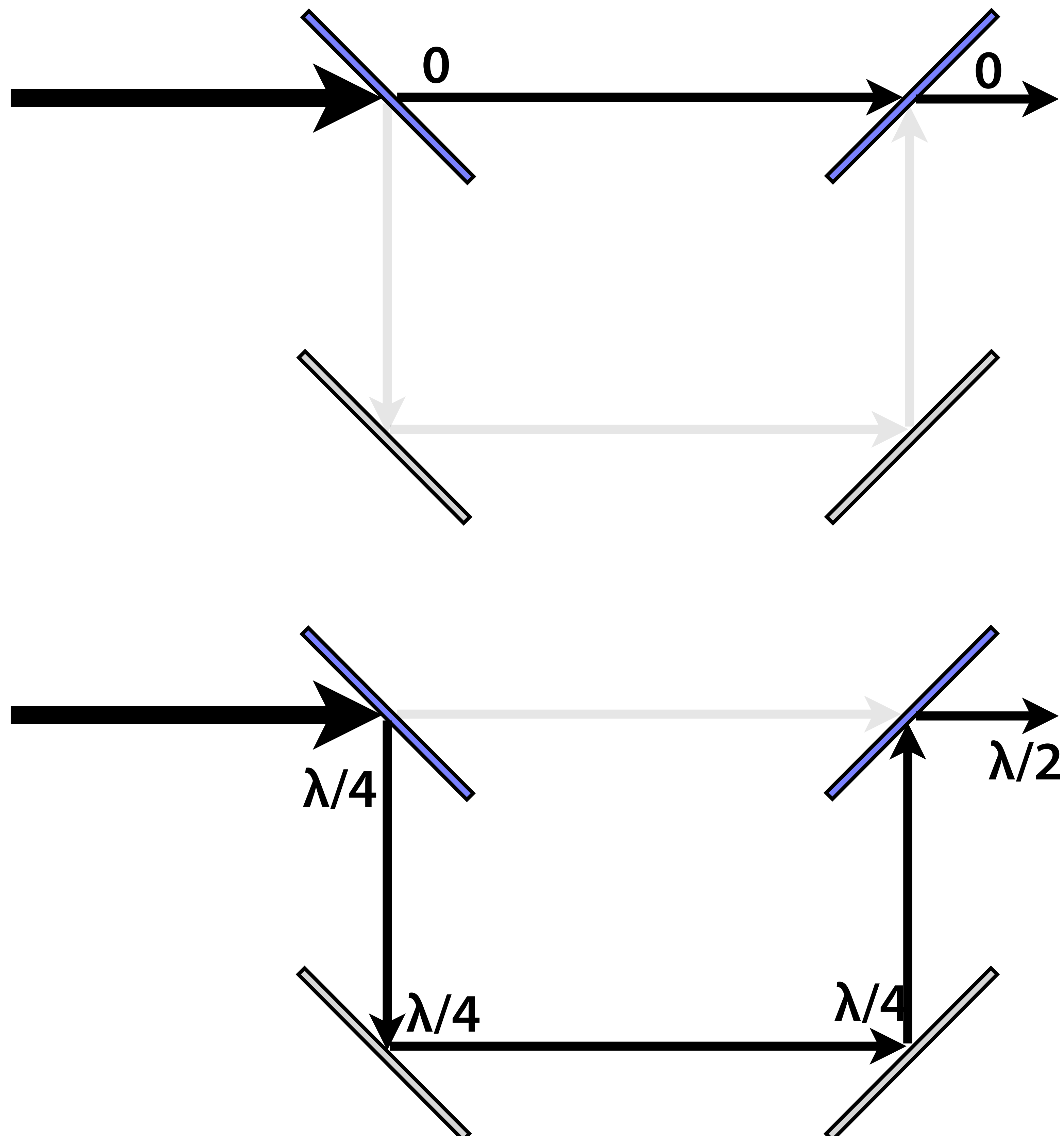
- We can see why by considering the phase shifts on each path.
- First to the **top detector.**
- In both paths, there is just **one** reflection **in** a beam splitter.
- The paths have **same** phase shift.
- **In-phase** waves **constructively** interfere.





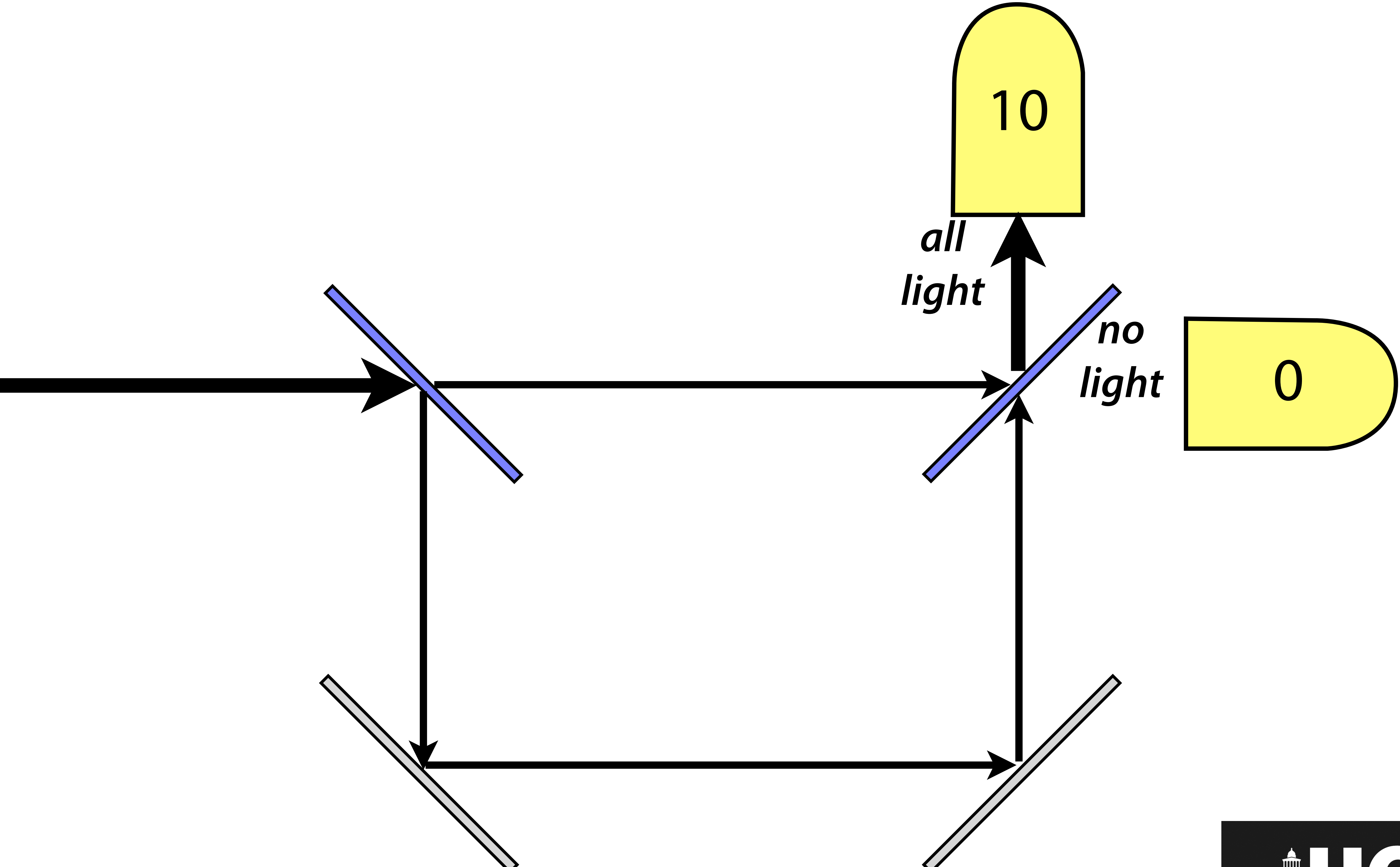
Mach-Zehnder Interferometer

- Now we consider the to the **right detector.**
- In the upper path, there are **no reflections.**
- In the lower path there are **two reflections.**
- The lower path has a phase shift of **λ/2,** while the upper path has **no phase** shift.
- The waves from the two paths are **in antiphase**, and hence we see **destructive** interference.



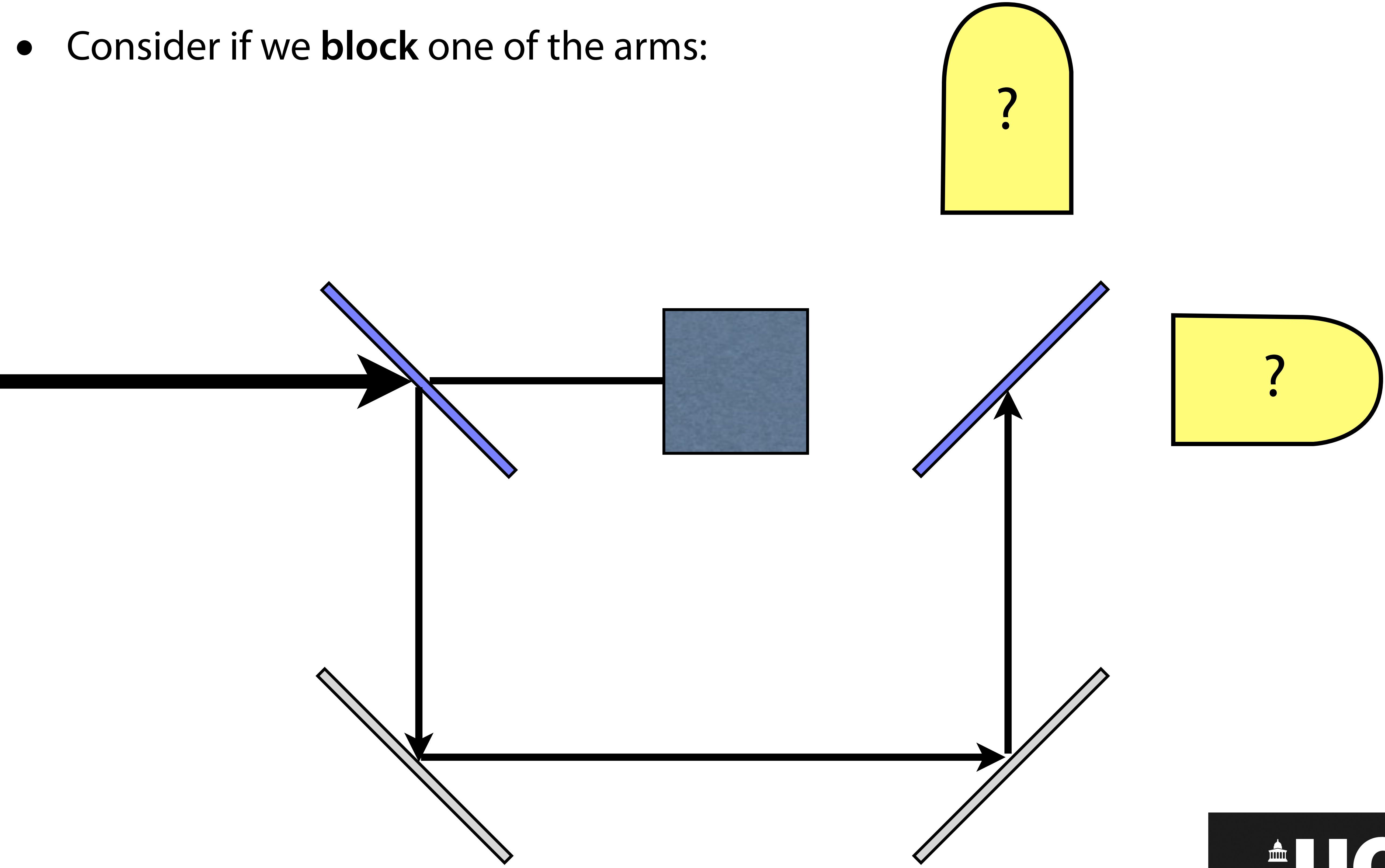
Mach-Zehnder Interferometer

- A particle picture cannot explain this.



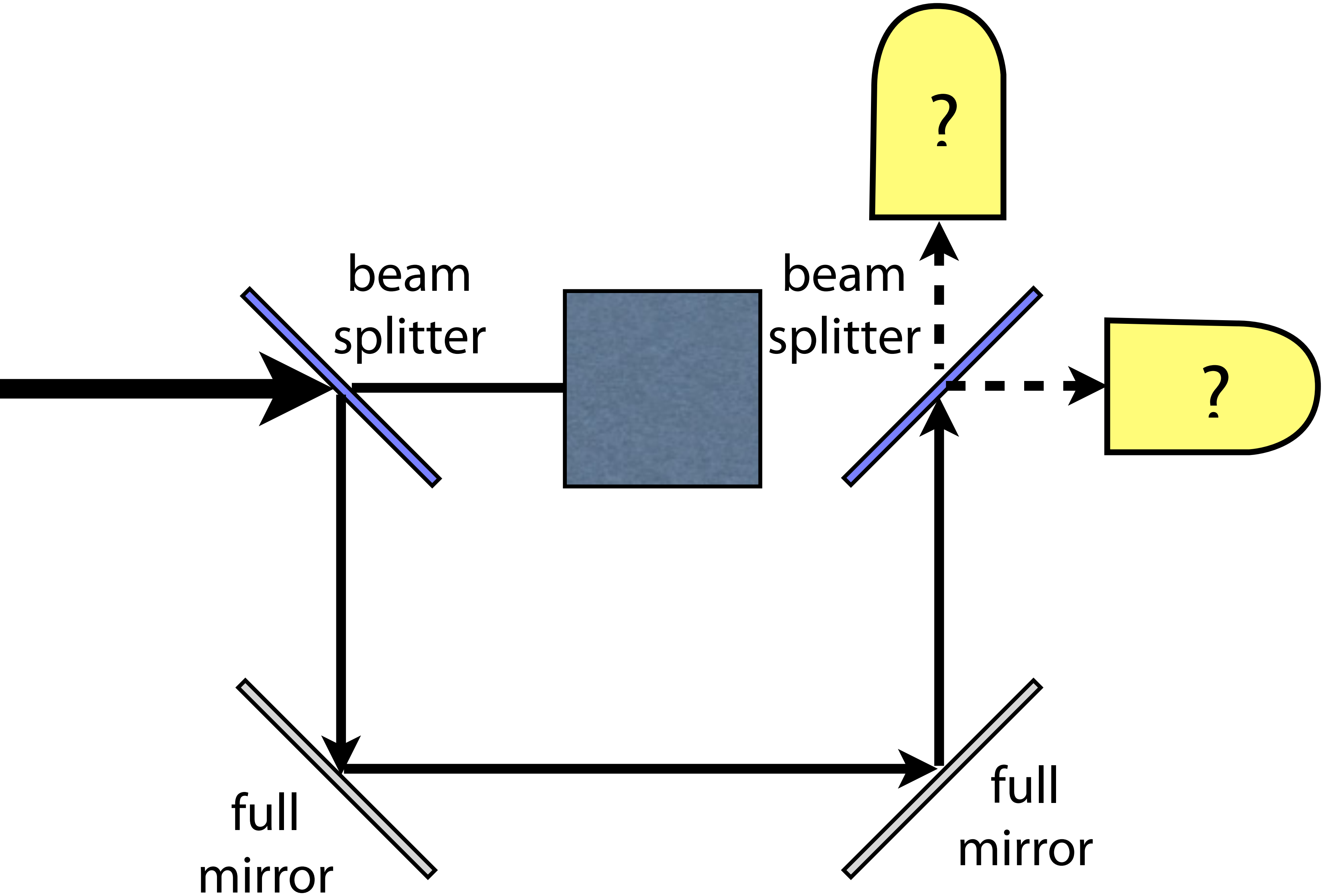
Mach-Zehnder Interferometer

- A particle picture cannot explain this.
- Consider if we **block** one of the arms:

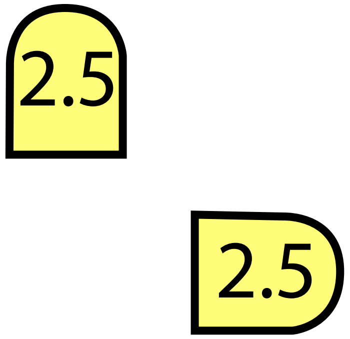


Quiz

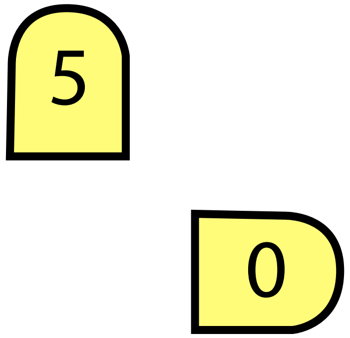
- With **10W input** and an **obstruction in the top path** what do you expect to see on the detectors?



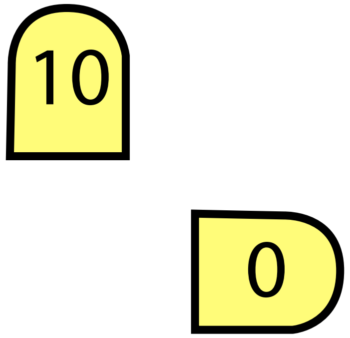
- **1.**



- **2.**

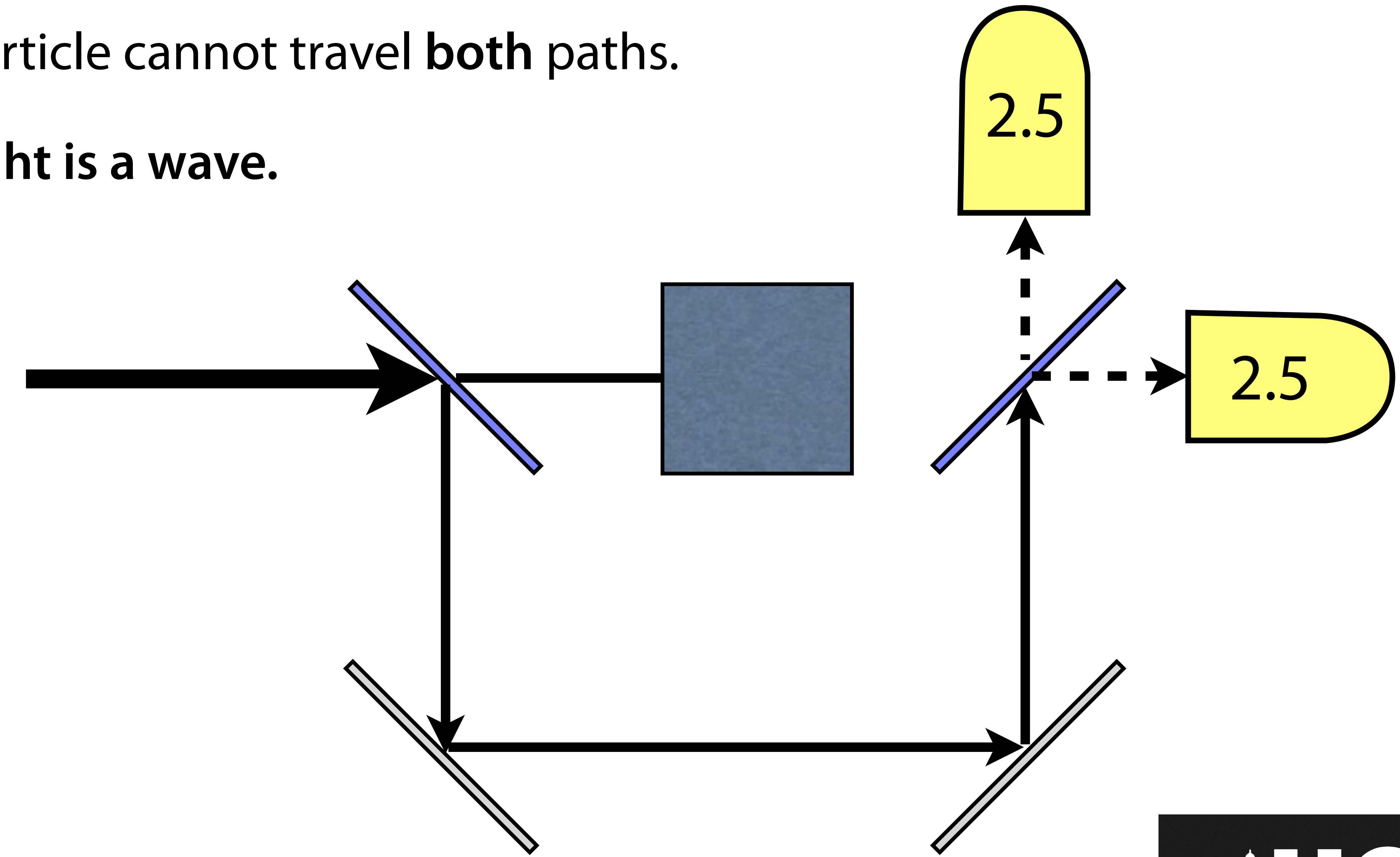


- **3.**

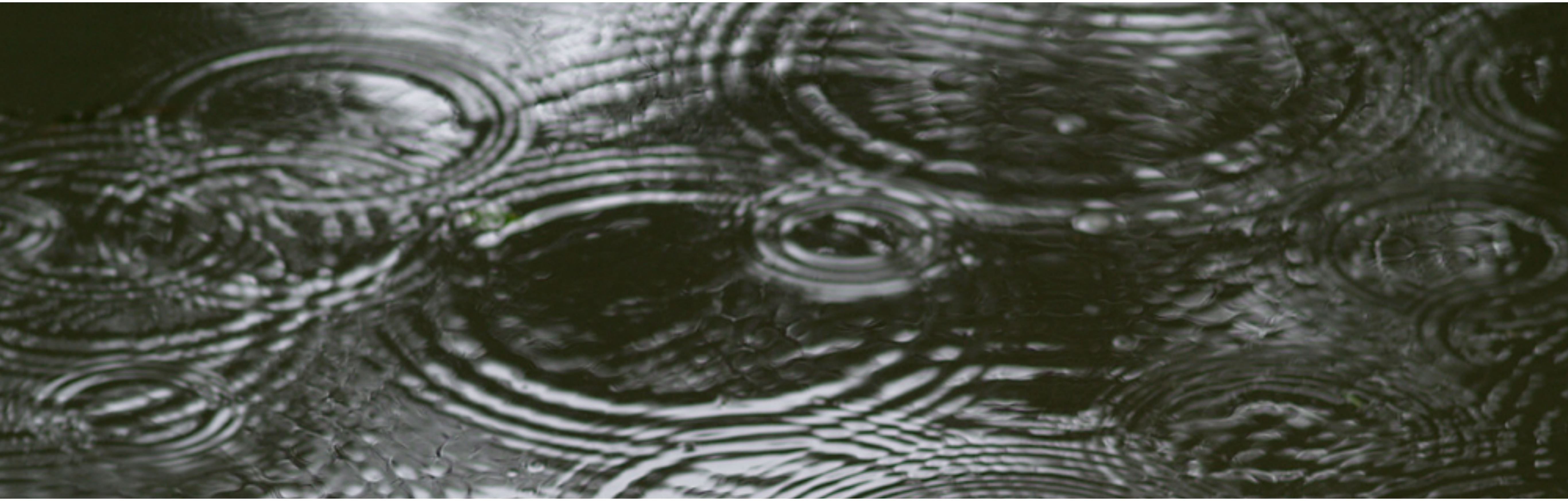


Mach-Zehnder Interferometer

- If we obstruct **one** of the paths **both** detectors change their value.
- Same is true if other path blocked instead.
- Light at each detector "knows" about **both paths.**
- A classical particle cannot travel **both** paths.
- **Therefore light is a wave.**

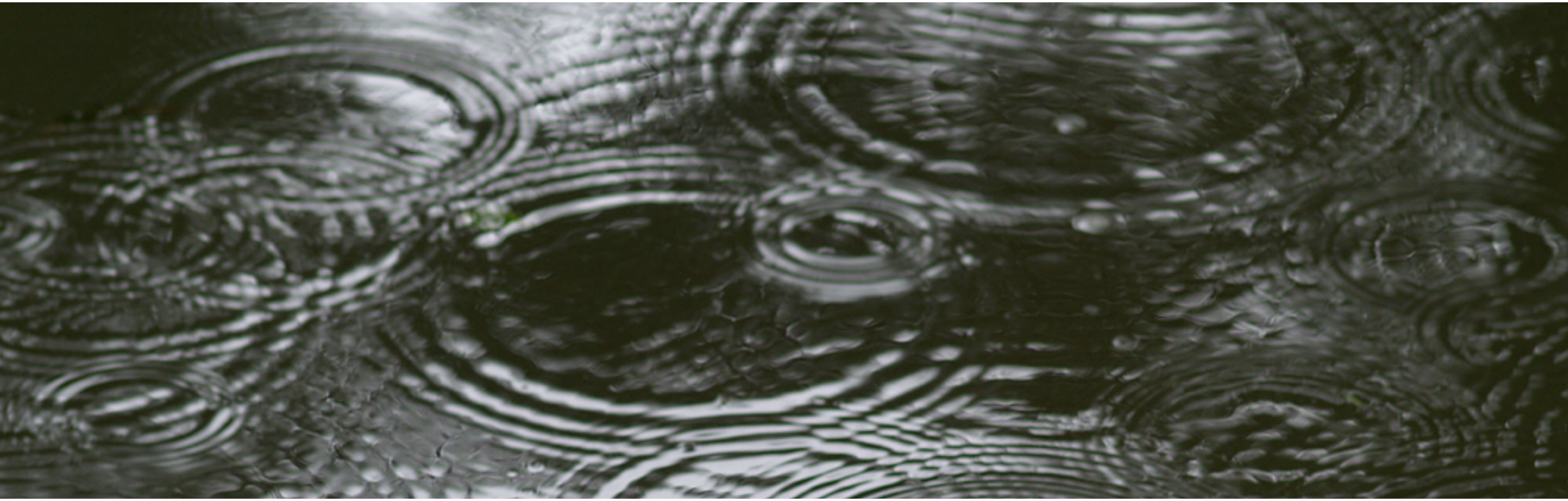


Problems with the wave picture



Problems with the wave picture

- The Young double slit experiment and the Mach-Zehnder both seem **irrefutable evidence** that **light** is a **wave**.



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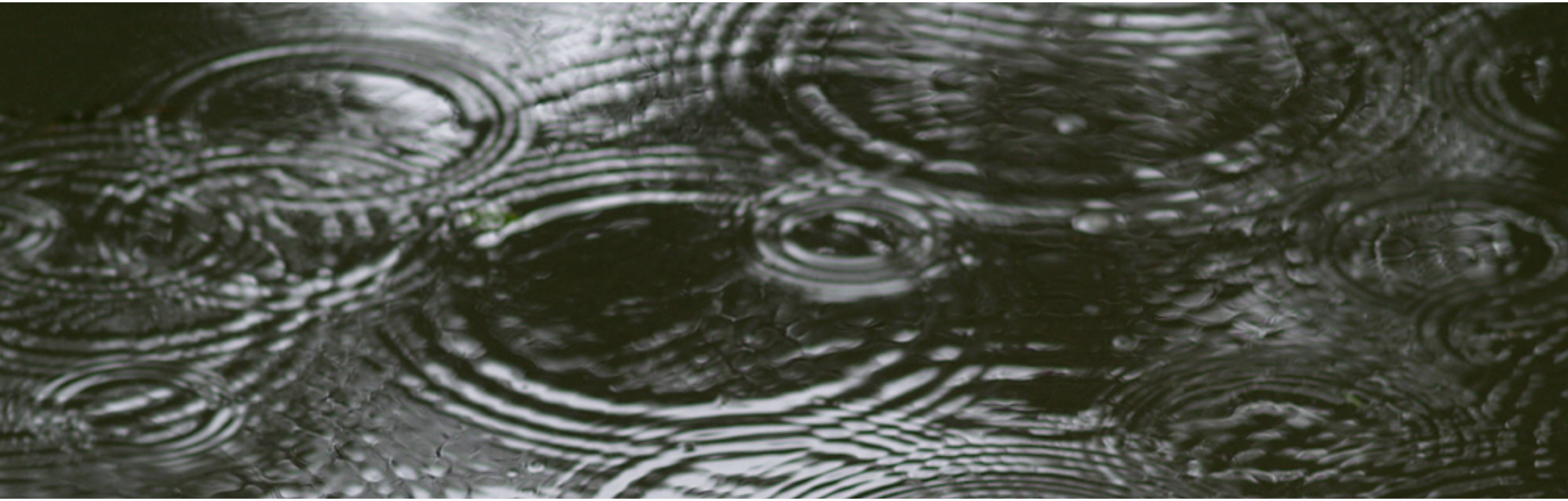

- Fortunately Physics is **more interesting** than that!

Problems with the wave picture

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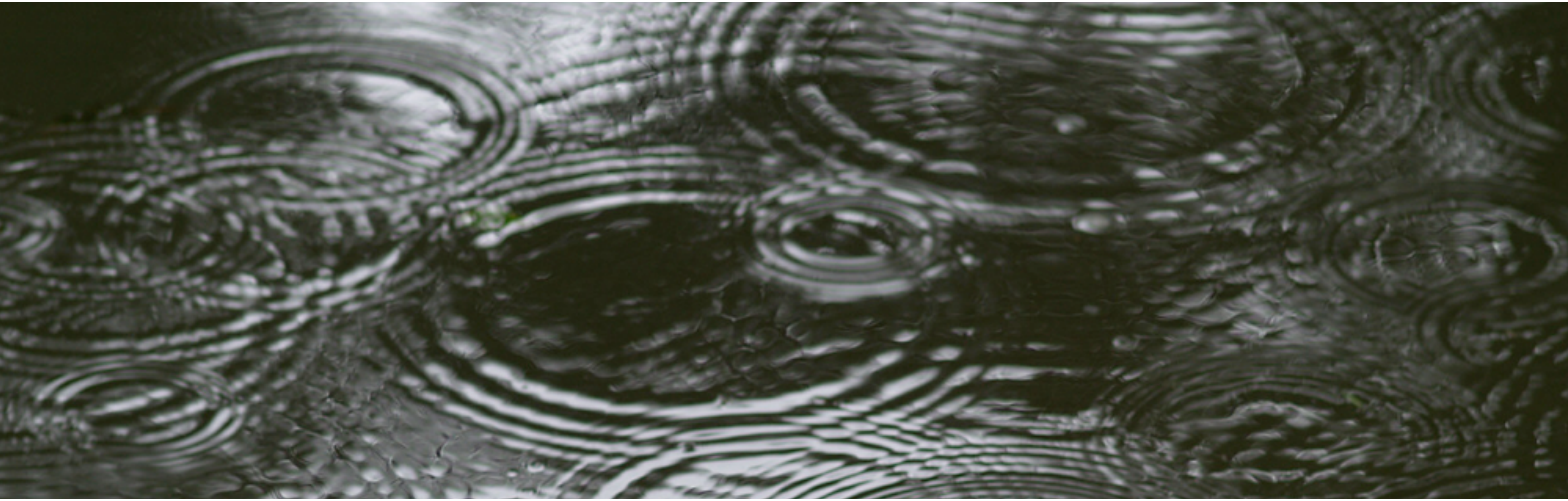
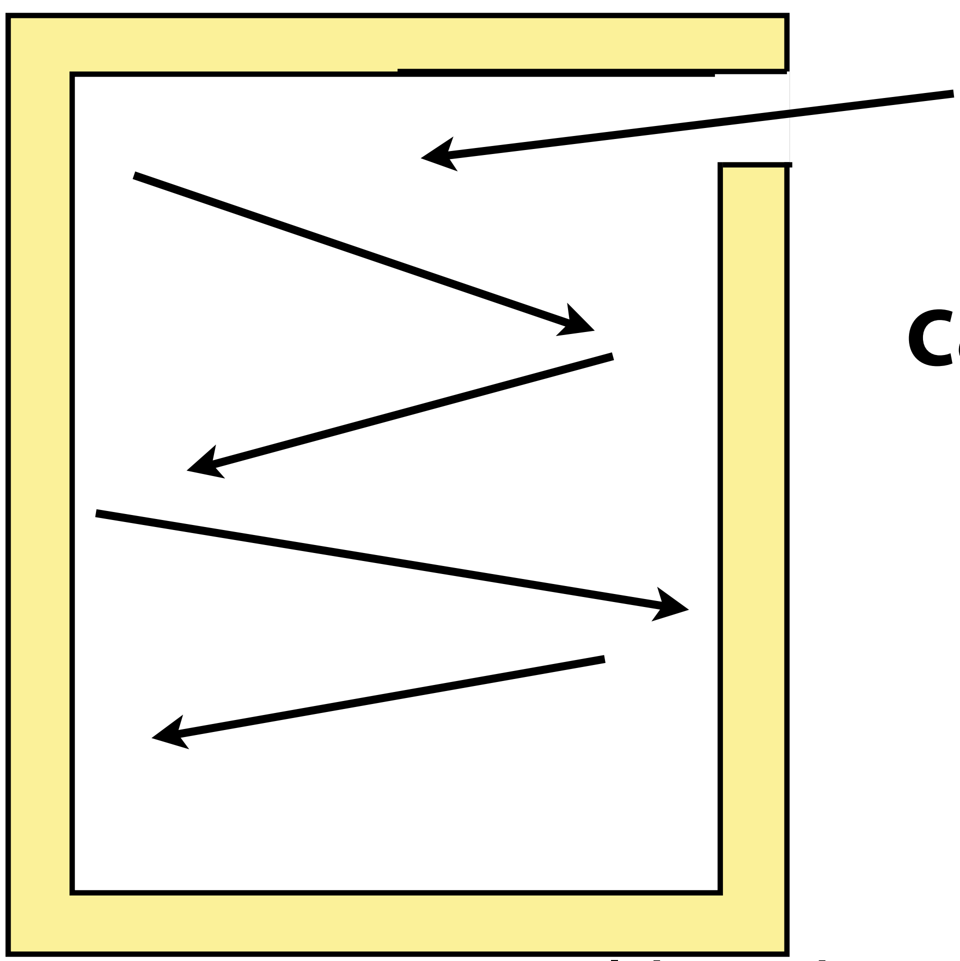


- Fortunately Physics is **more interesting** than that!
- In the first decade of the 20th century, **strong evidence** started to build that the wave picture is **not** the whole story.

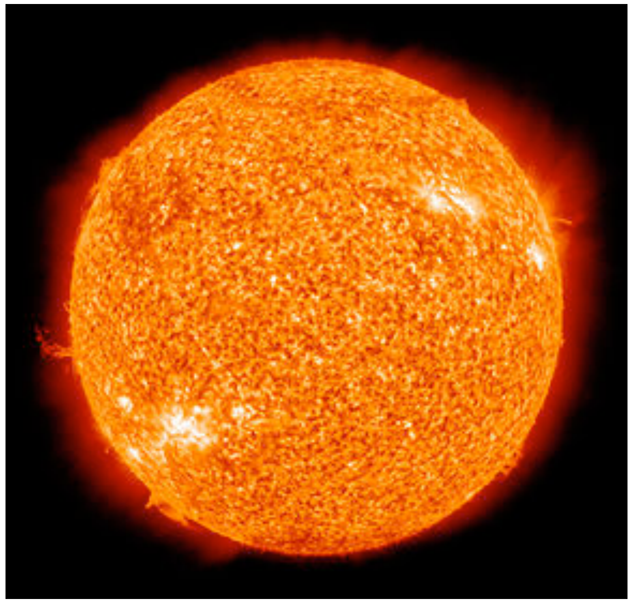
Black-body radiation

- A black body is an idealised object which absorbs **all light** incident on it.

- E.g. a box with a **very small hole**.



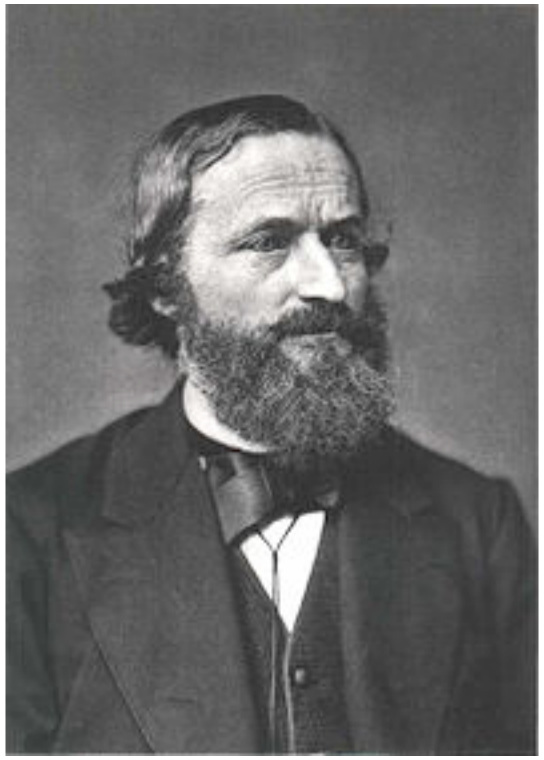
Light entering cannot leave



- Although an idealisation, **many** physical objects behave approximately like a **black body**.

UCL

Black-body radiation



Gustav Kirchoff

- The black body was the simplest idealised system for 19th century physicists struggling to understand **absorption** and **radiation** of light.

- Kirchoff's Challenge: (1862)

  - **experimentally measure** and

  - **theoretically understand** black body radiation.

- ***To solve this became one of the key goals of 19th c. Physics!***

Black-body radiation

- **Experimental Data**
  - By measuring the emission of light from black-bodies at different temperatures they established:
  - **Stefan's law**

$$P = \sigma A T^4$$

    - **P:** Total power (Joules per second) radiated.
    - **A:** Surface area of black body (m^2)
    - **T:** Temperature (Kelvin)
    - **σ:** Stefan's constant, $\sigma = 5.7 \times 10^{-8}$ W/m^2

- Still used by astronomers (will feature in second half of this course).

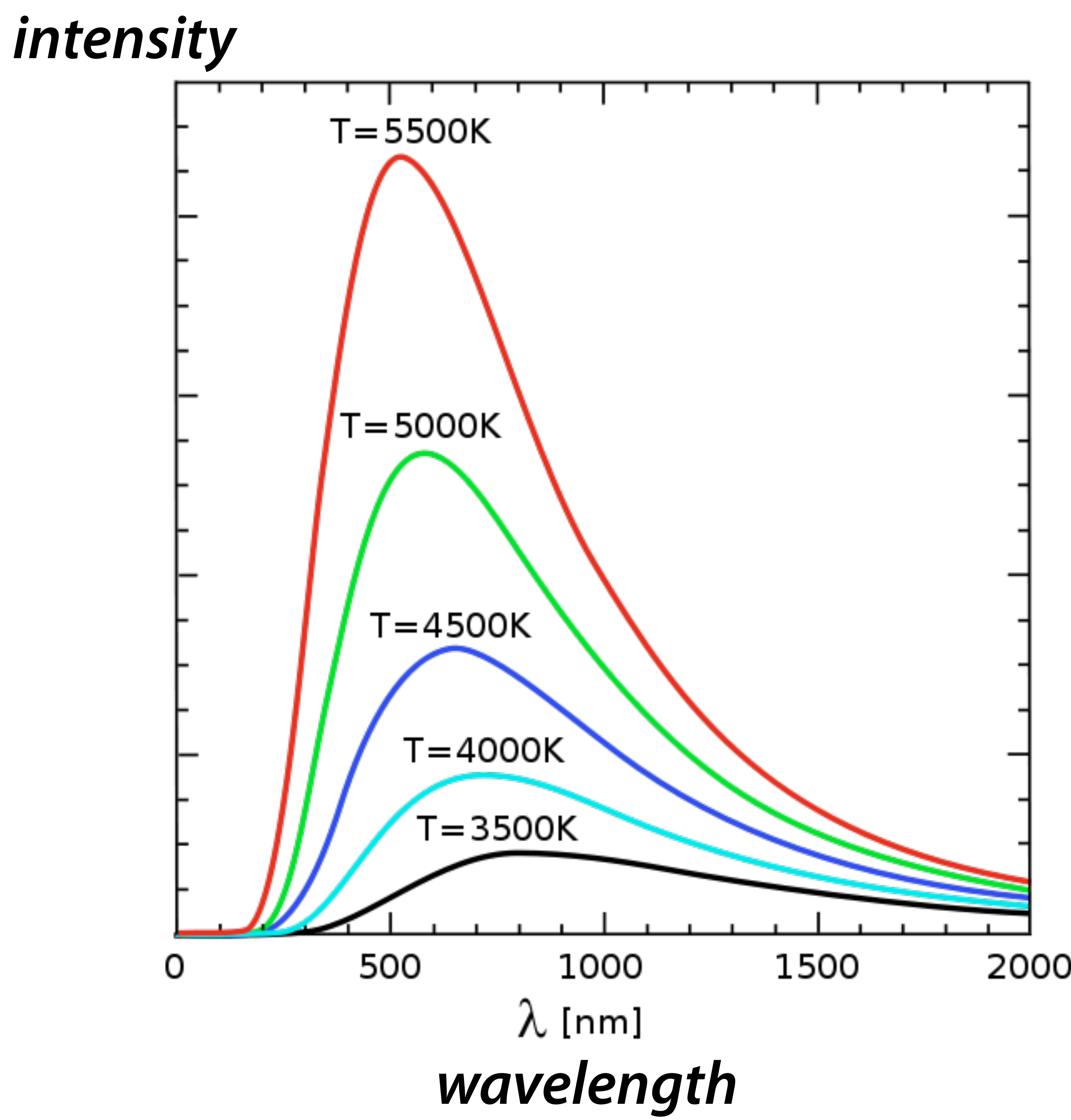
Black-body radiation

- **Experimental Data**
  - The full spectrum of emitted light could be measured, as a function of temperature.
  - **Wien's law**
    - The **peak wavelength λ_{max}** of the radiation is **inversely proportional** to **temperature T**.

$$\lambda_{\mathrm{max}} = \frac{2.9 \times 10^{-3}\ \mathrm{m\ K}}{T}$$

- "The hotter, the bluer".
- Also used by astronomers - star colour indicates temperature.

Black-body emission spectra



Black-body radiation

- Aim: A theoretical derivation of these curves.

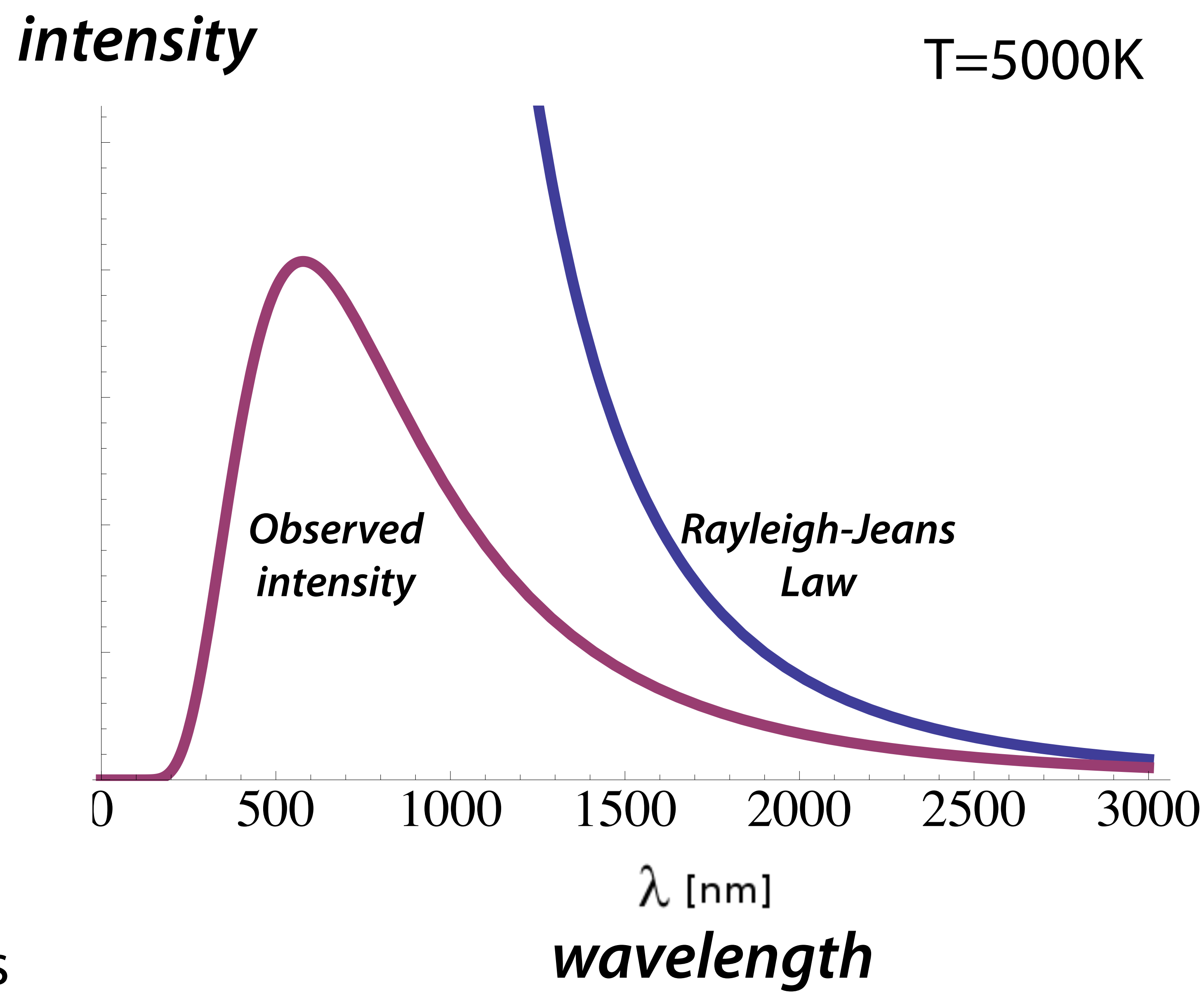
- Best attempt: **Rayleigh-Jeans law**

$$I(\lambda, T) = \frac{2\pi\, c\, k\, T}{\lambda^4}$$

  - **c** is the speed of light,
    k is Boltzmann's constant,
    T is temperature, and
    λ is wavelength

- Derivation used thermodynamics and wave model of light. *(See 2nd year Statistical Thermodynamics course).*

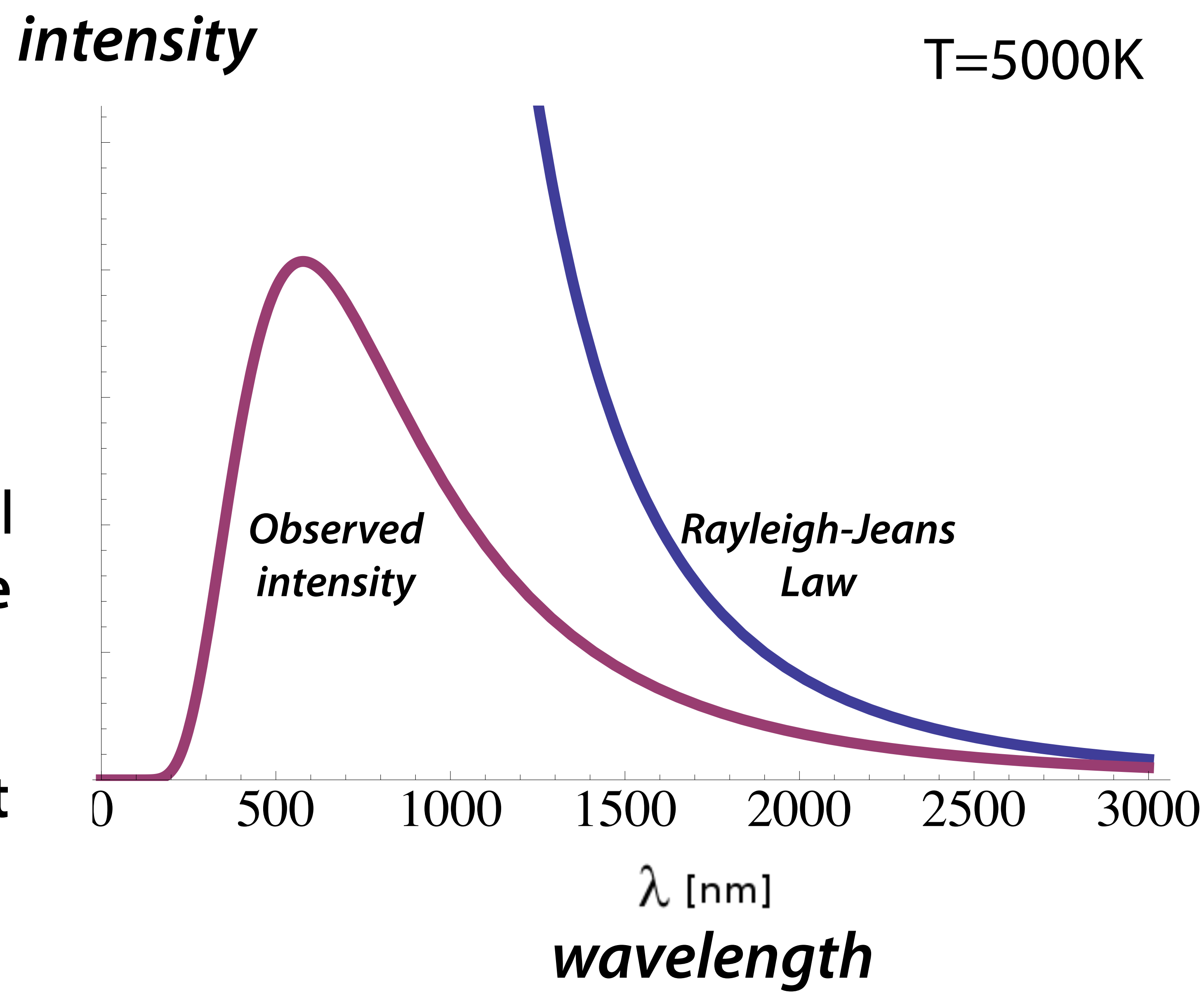
  - Key assumption - at all wavelengths light energy is absorbed and emitted **continuously**.



Black-body radiation

$$I(\lambda, T) = \frac{2\pi\, c\, k\, T}{\lambda^4}$$

- Rayleigh-Jeans law was unsatisfactory.
  - First - it didn't fit the data.
  - Even worse, it diverged for small wavelengths, predicting **infinite radiation** for very small **λ.**
  - This is known as the **ultra-violet catastrophe!**



Black-body radiation

- **Planck** (1900)
  - Initial Idea: A mathematical trick:
    - Assume light energy is absorbed and emitted in **discrete units.**
    - Each "unit" has energy proportional to its frequency.

$$E = hf$$

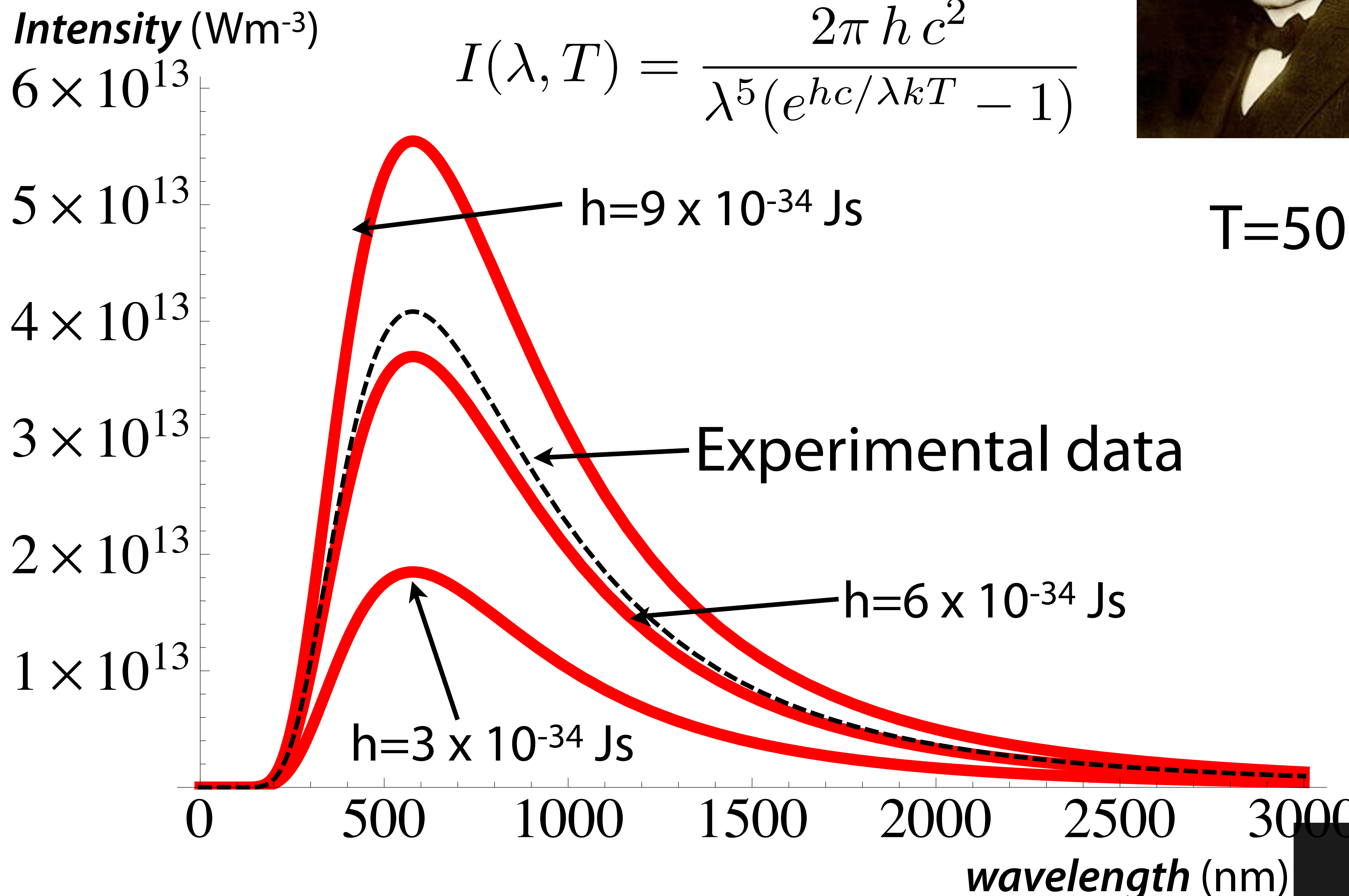
    - where ***f*** is **frequency** and **h** is a constant **to be determined**
  - The result: **Planck's law** (derived in 2nd year Thermal Physics)

$$I(\lambda, T) = \frac{2\pi\, h\, c^2}{\lambda^5 (e^{hc/\lambda kT} - 1)}$$

Black-body radiation

- **Planck's law** - for different h-values

$$I(\lambda, T) = \frac{2\pi\, h\, c^2}{\lambda^5 (e^{hc/\lambda k T} - 1)}$$



T=5000K

Black-body radiation

- ***Planck's constant***
  - Modern experiments have **measured h - Planck's constant -** to high accuracy:

$$h = 6.626 \times 10^{-34}\ \mathrm{Js}$$

  - In research-level Physics, we often use "hbar" :

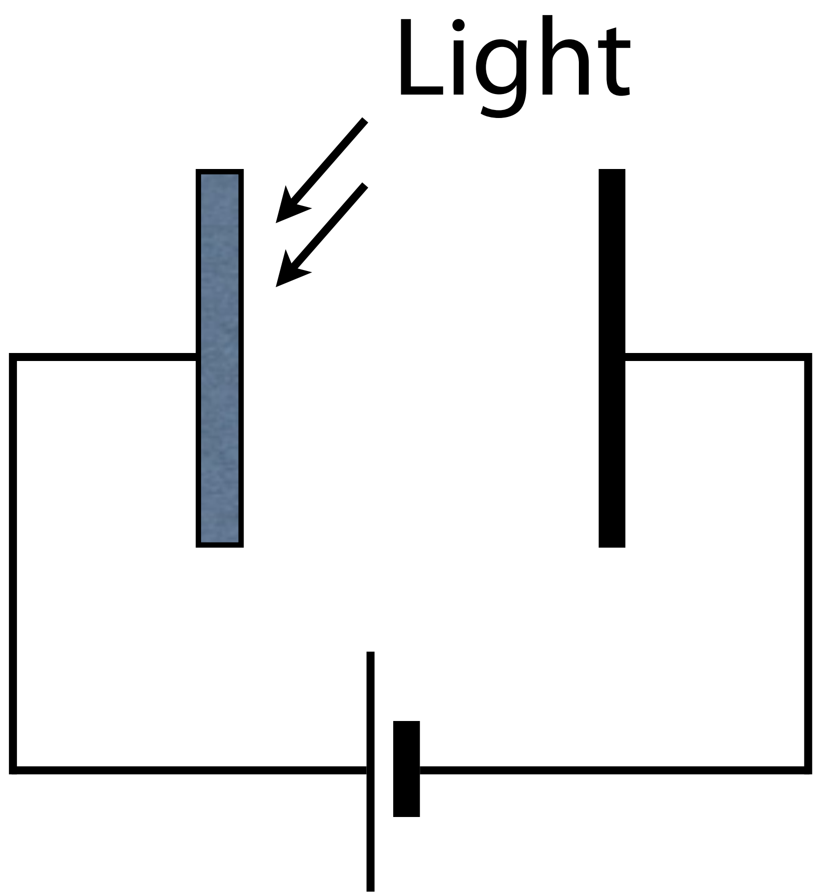
$$\hbar = \frac{h}{2\pi} = 1.055 \times 10^{-34}\ \mathrm{Js}$$

  - The success of Planck's law seemed mysterious. It was known that light was a wave.
  - Yet in Planck's derivation, light behaved as if in discrete "**packets**" of energy.

$$E = hf = \hbar\omega$$

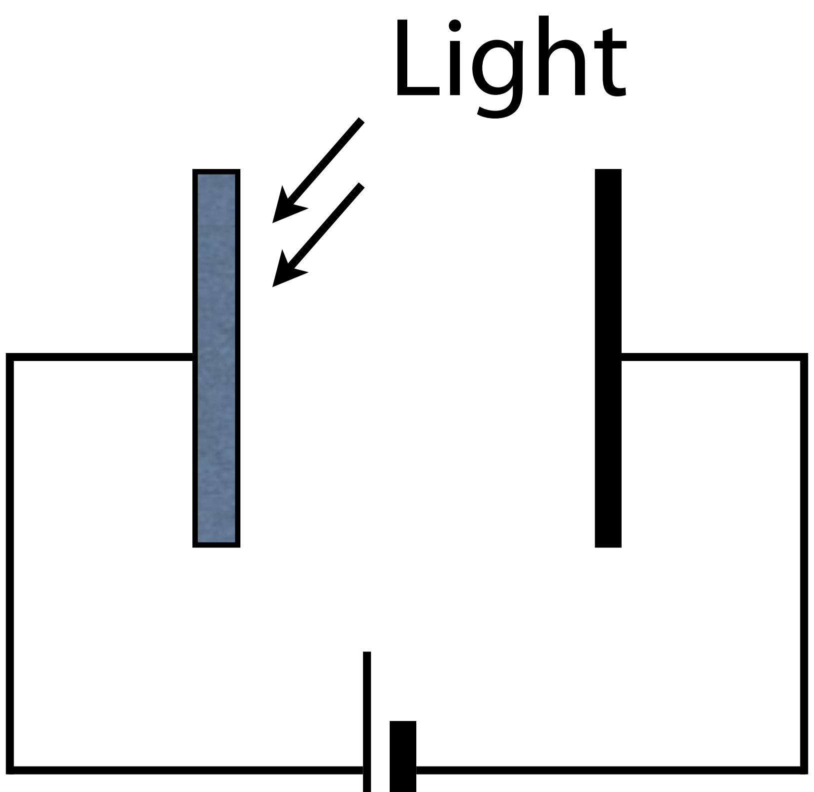
  - where ω is **angular frequency** ω **=** 2 π f

Photo-electric effect

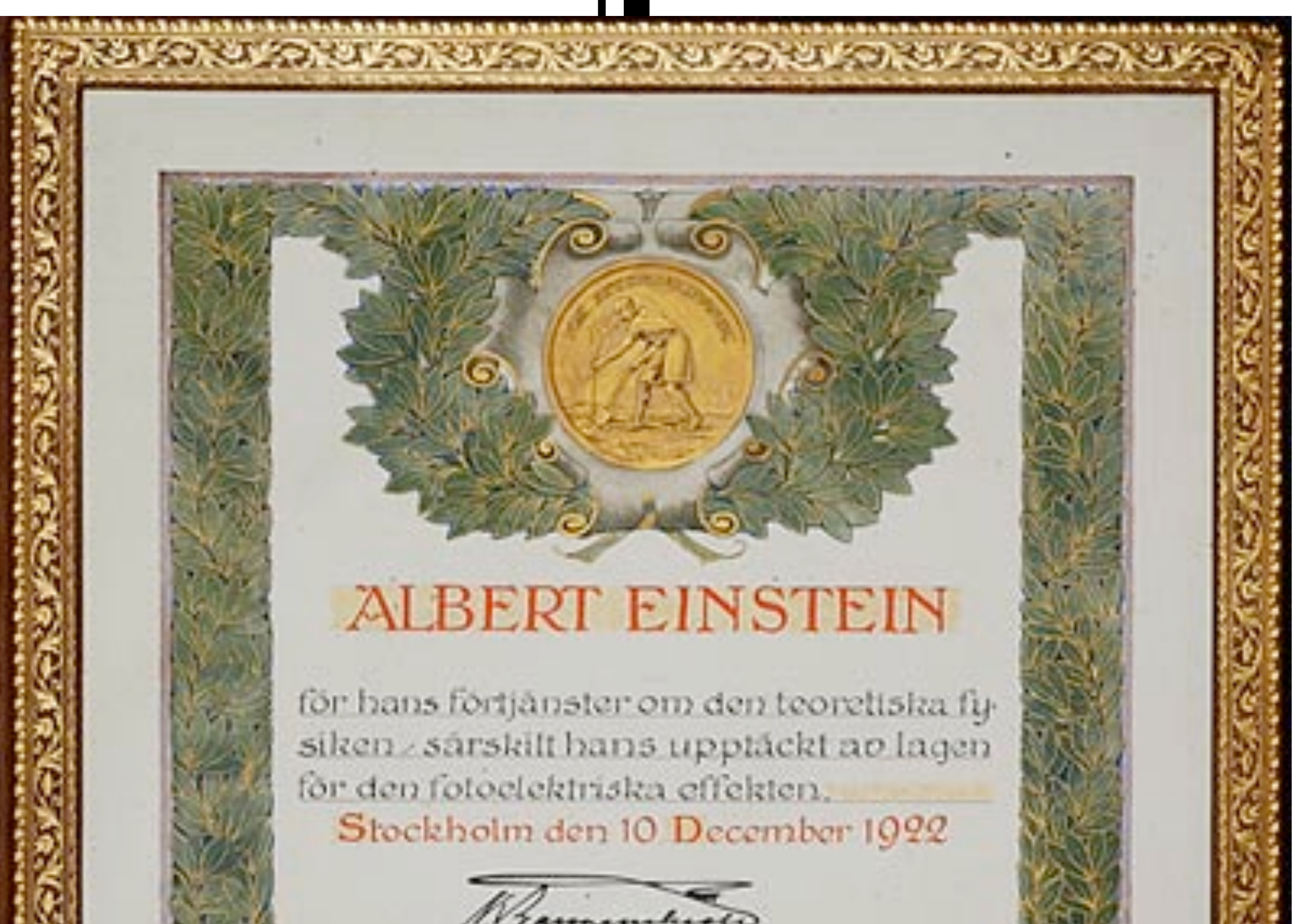


- **Experimental Observations**
  - When incident light is above a **threshold frequency**, current flows, proportional to intensity.
  - When incident light is below the **threshold frequency**, no current flows.

Photo-electric effect



- **Einstein's idea**
  - Take Planck's model seriously.
  - Assume light consists of **particles** of energy hf = $\hbar\omega$
  - Electrons can only absorb energy from one photon at a time.
  - Each electron has a minimum **binding energy** ("work function") which it needs to receive to escape the material and travel round the circuit.



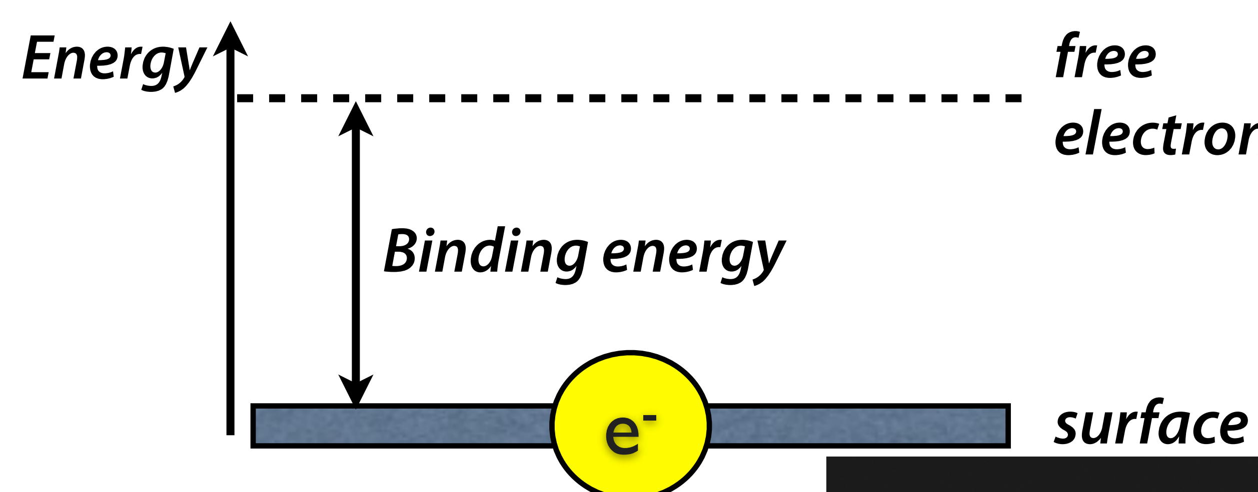
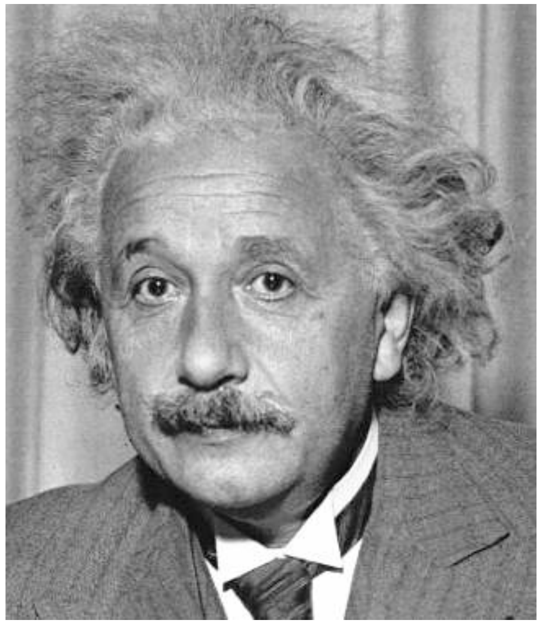


Photo-electric effect

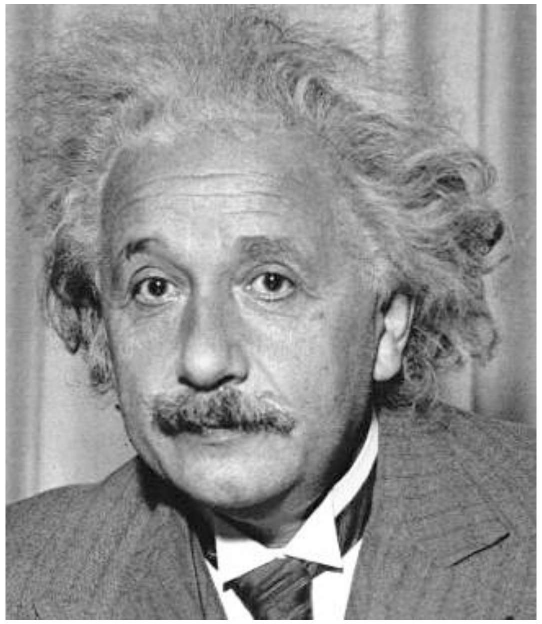


- Einstein's model explained **all** features of the photo-electric effect.
- But could the **wave picture** of light be given up so readily?
- But Young's **wave evidence** was **very strong**. Perhaps the photo-electric effect had **another explanation**?
- To convince the bulk of physicists more **persuasive evidence** was needed.

Photon Momentum

- The answer lay in photon **momentum**
  - (In part due to another contribution of Einstein!)
- Classical mechanics:
  - **Waves** have momentum
  - **Light** has momentum
    - (consequence of electromagnetic theory - 2nd year EM course)
  - Therefore **photons** must have **momentum** too.

Photon Momentum



- Special relativity (1905)
  - **Massless particles** travel at the **speed of light**.
  - Massless particles carry **momentum** - given by:

$$p = \frac{E}{c}$$

    - (Related to $E=mc^2$ which holds for particles with mass)
- The photon is a massless particle with **energy**

$$E = hf$$

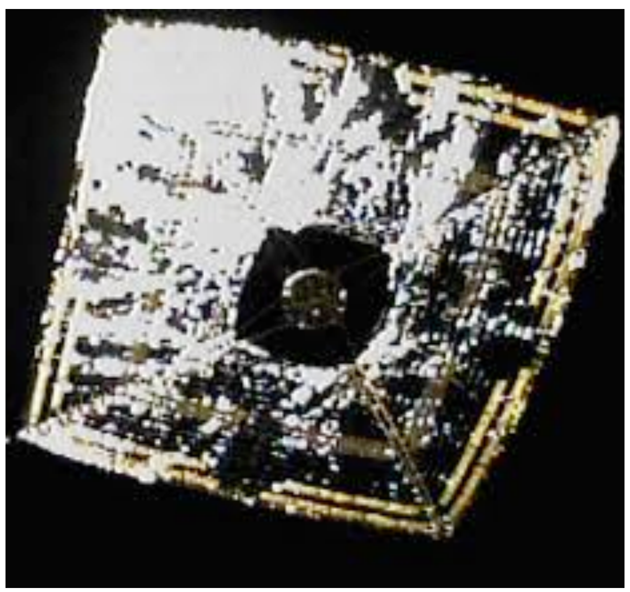
- and therefore **momentum**

$$p = h\frac{f}{c} = \frac{h}{\lambda}$$

Photon Momentum

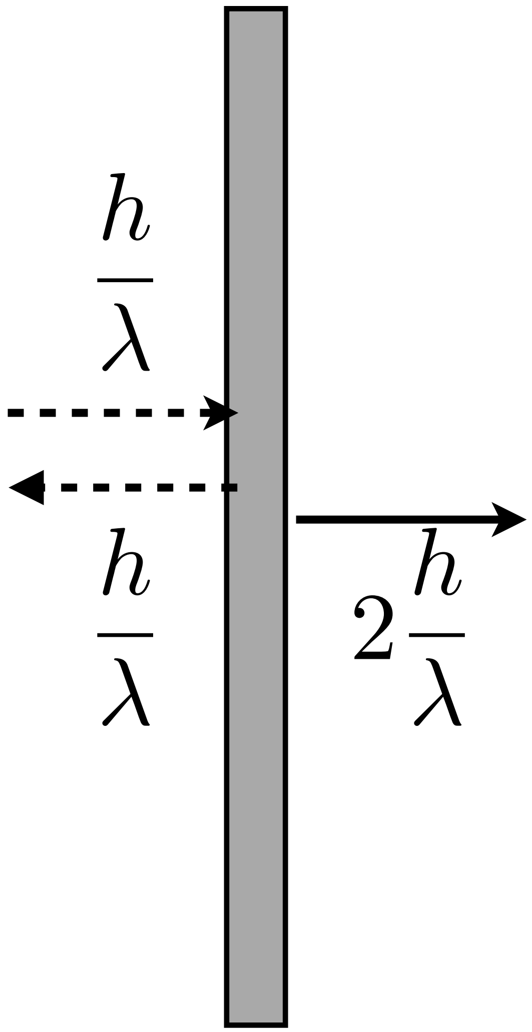
- Every photon carries momentum:

$$p = \frac{h}{\lambda}$$



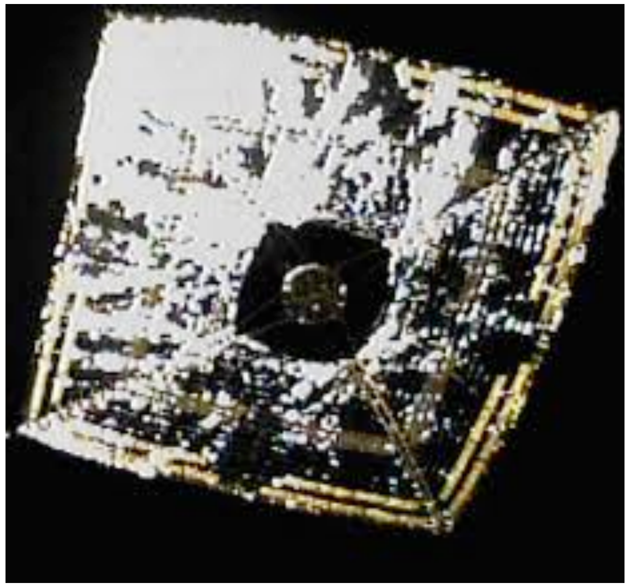
IKORAS
Venus
probe

- Thus reflecting light exerts **pressure**.
- The physics behind **solar sails**.
- Each photon reflected imparts a **momentum kick** to the sail, accelerating the probe.



Quiz

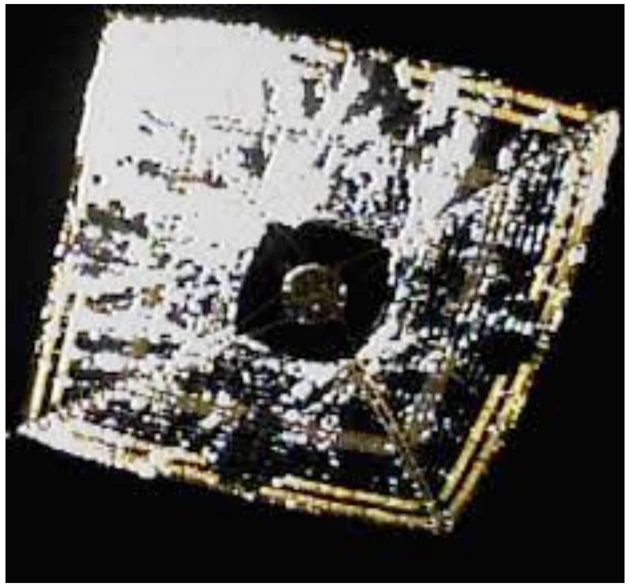
- Is **radiation pressure** evidence for the **particle** nature of light?



- 1. Yes
- 2. No

Quiz

- Is **radiation pressure** evidence for the **particle** nature of light?



  - 1. Yes
  - **2. No**

- Classical electromagnetism predicts the **same** radiation pressure when light reflects from **macroscopic objects**.

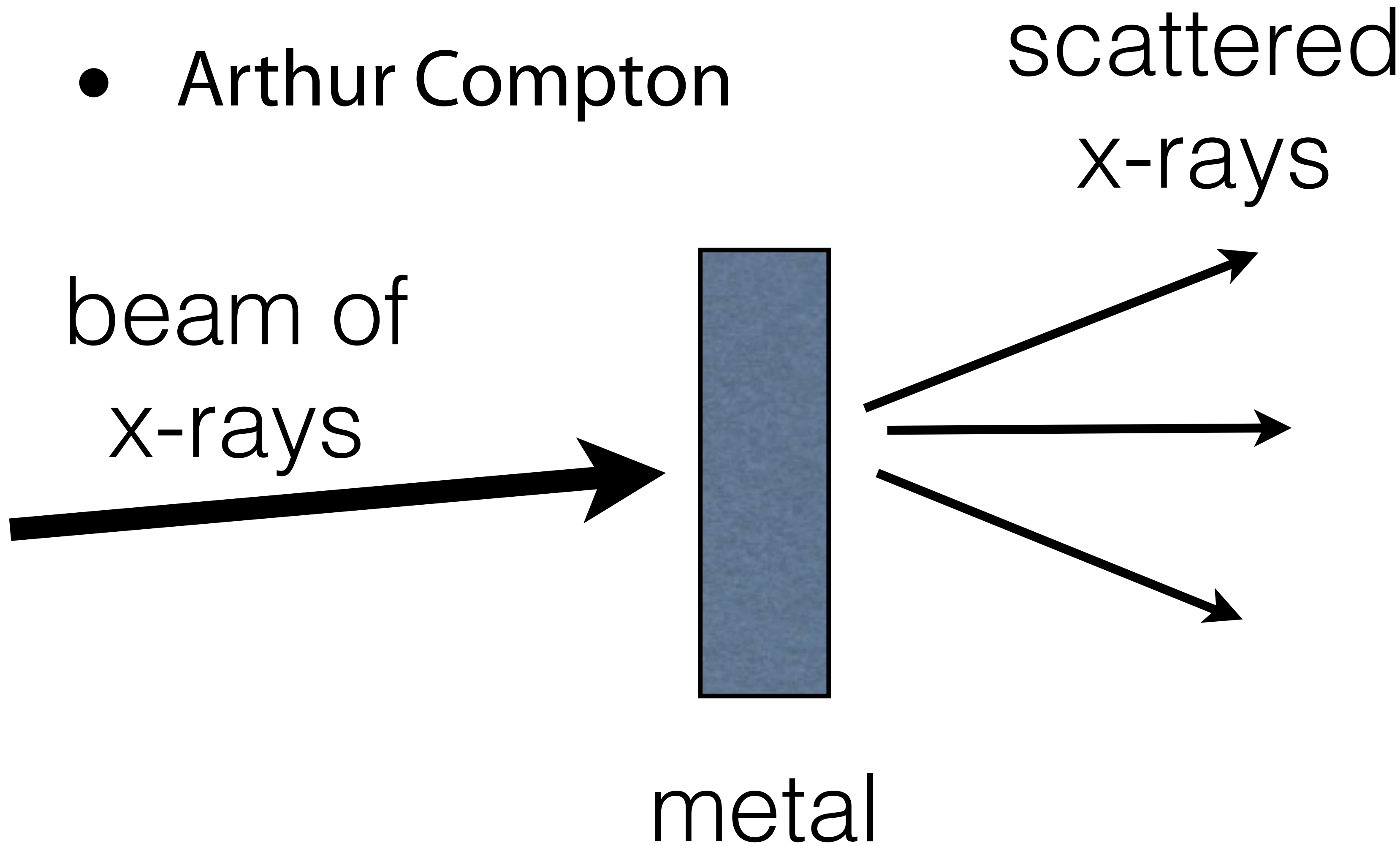
Arthur Compton

- This is **not true** for microscopic charged particles.
  - In interaction with **single charged particles** (e.g. electrons).
  - **Classical electromagnetism** and **photon picture** give **very different** predictions.
- This is called the **Compton Effect.**

The Compton Effect

- ***1922 - Compton Scattering***
  - Arthur Compton

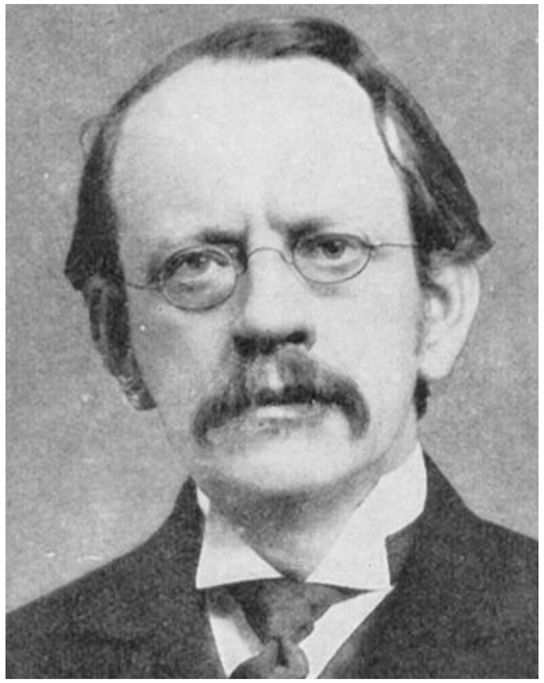
Arthur Compton



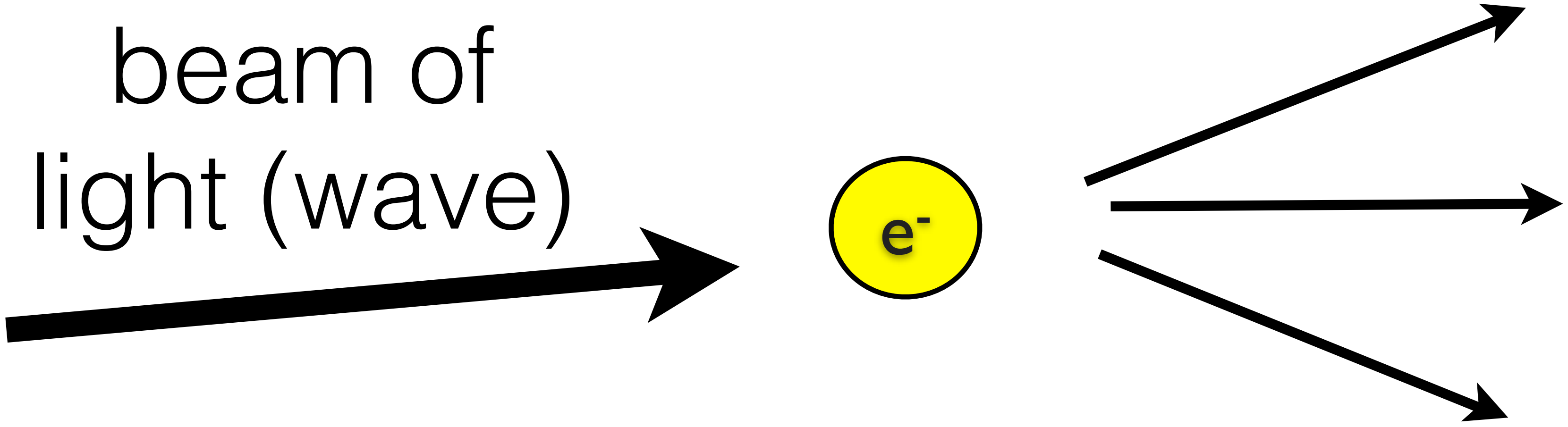
- When **X-rays** (nm light) are incident on a metal, they **scatter** from the **free electrons** in the metal.

The Compton Effect

- ***Thomson scattering (1900s)***
  - Thompson developed a theory for how **electromagnetic waves** should **scatter** from **charged particles**.

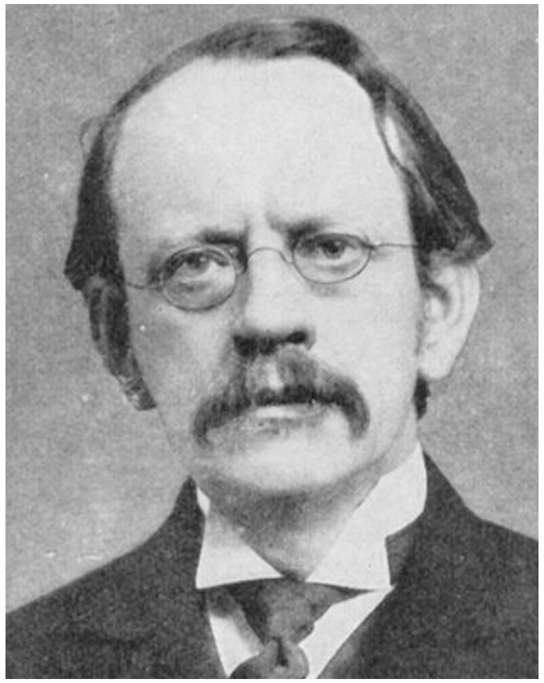


J.J. Thomson



The Compton Effect

- ***Thomson scattering (1900s)***
    - Key features:
        - The incoming wave (frequency **f=c/λ**) induces charged particle to oscillate at **same frequency** f.
        - Oscillating particle emits light at the **same frequency** f in all directions.
- An important effect in Plasma physics.



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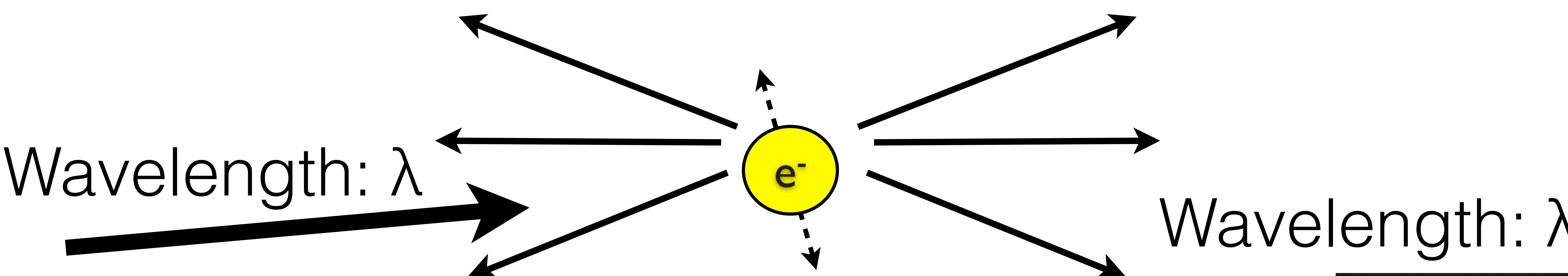
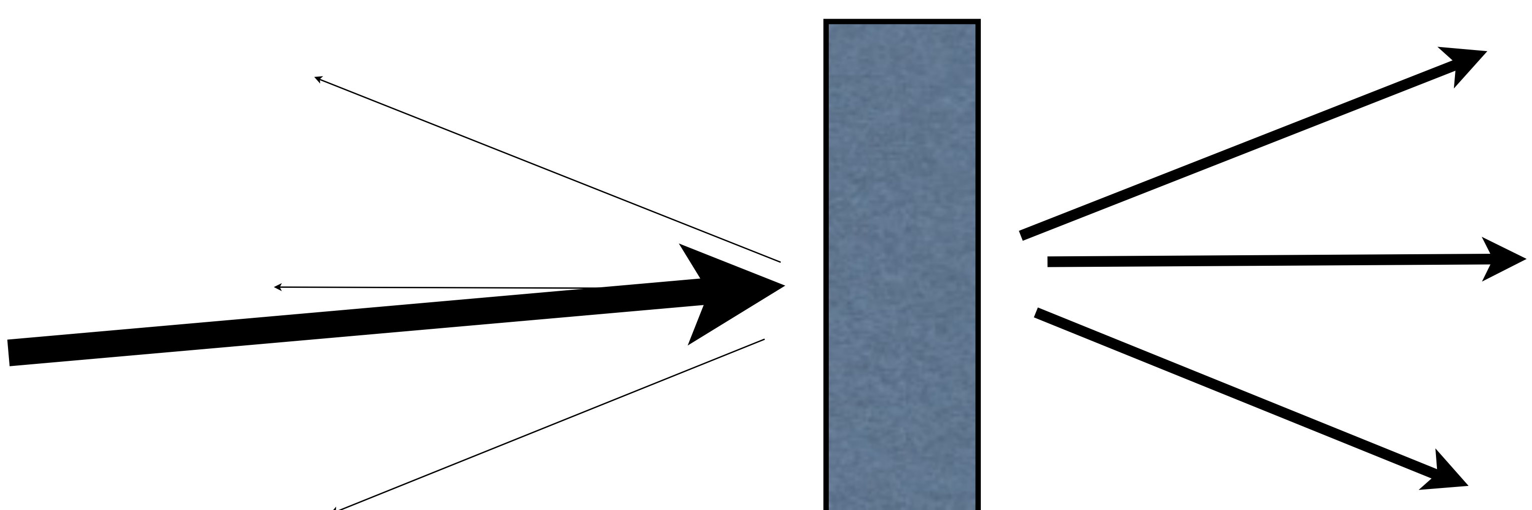


The Compton Effect

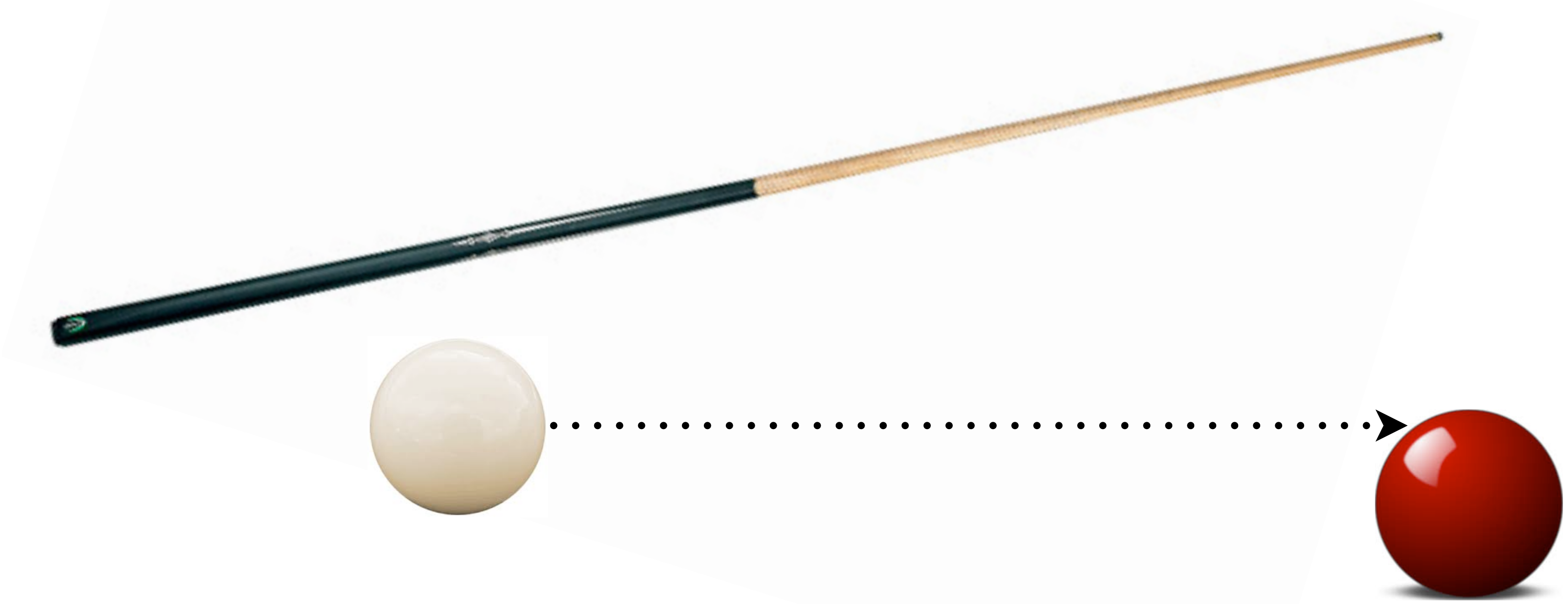
Arthur Compton

- ***1922 - Compton Scattering***
  - Thomson scattering was the classical theory of X-ray scattering.
  - But **high energy X-ray** scattering experiments did **not match** Thomson's predictions in several ways.
    - E.g. back-scattered light was **weaker** than Thomson predicted.
    - Scattered light experienced an **angle-dependent frequency shift**.



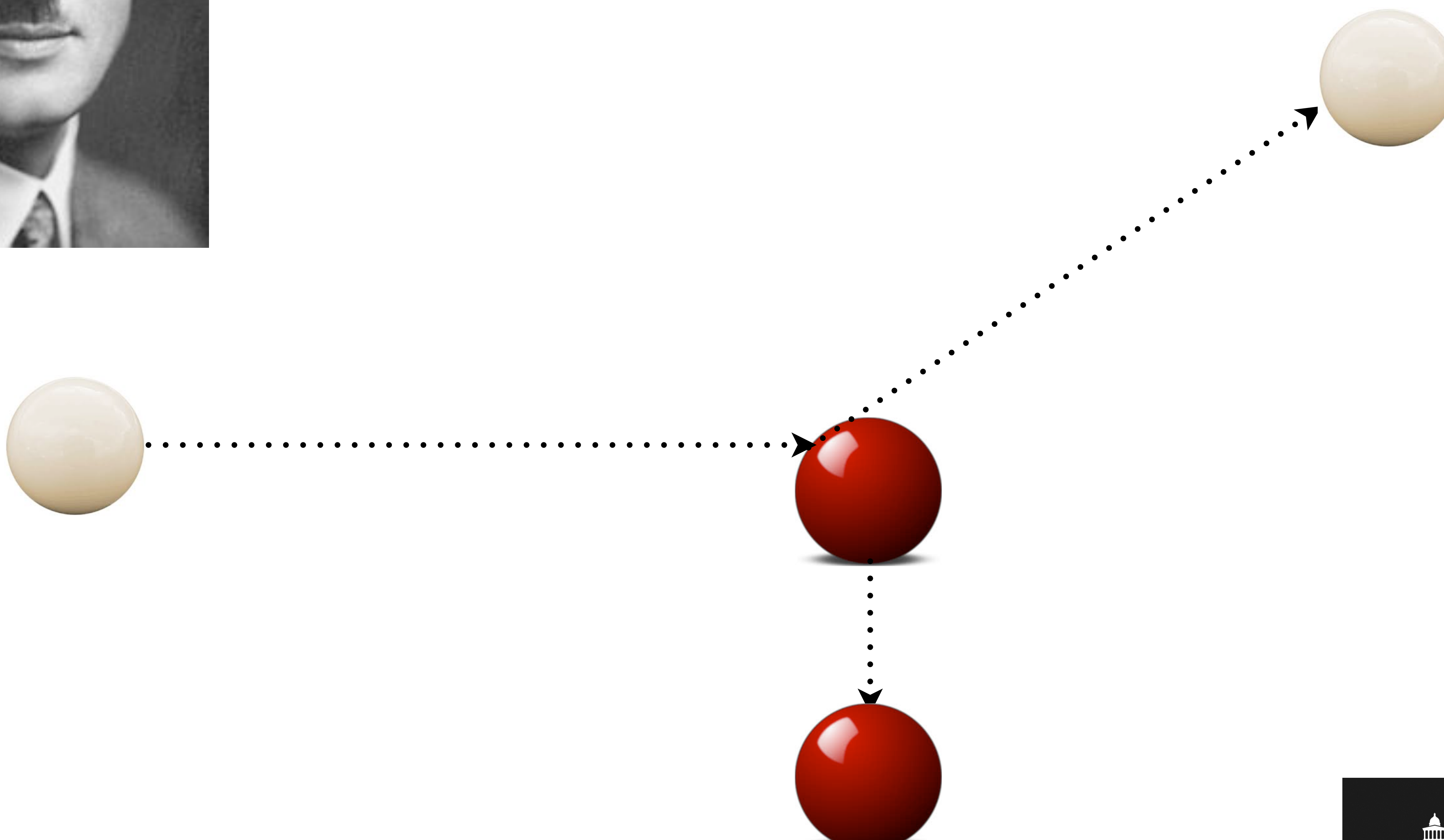
The Compton Effect

- ***1922 - Compton Scattering***
  - Compton's proposal:
    - Take **Planck** and **Einstein** seriously.
  - Treat incoming x-ray as a stream of **particles**.
  - Model scattering as an **elastic collision.**



The Compton Effect

- *1922 - Compton Scattering*
  - Elastic collision:
    - **Momentum** and **energy** conserved.



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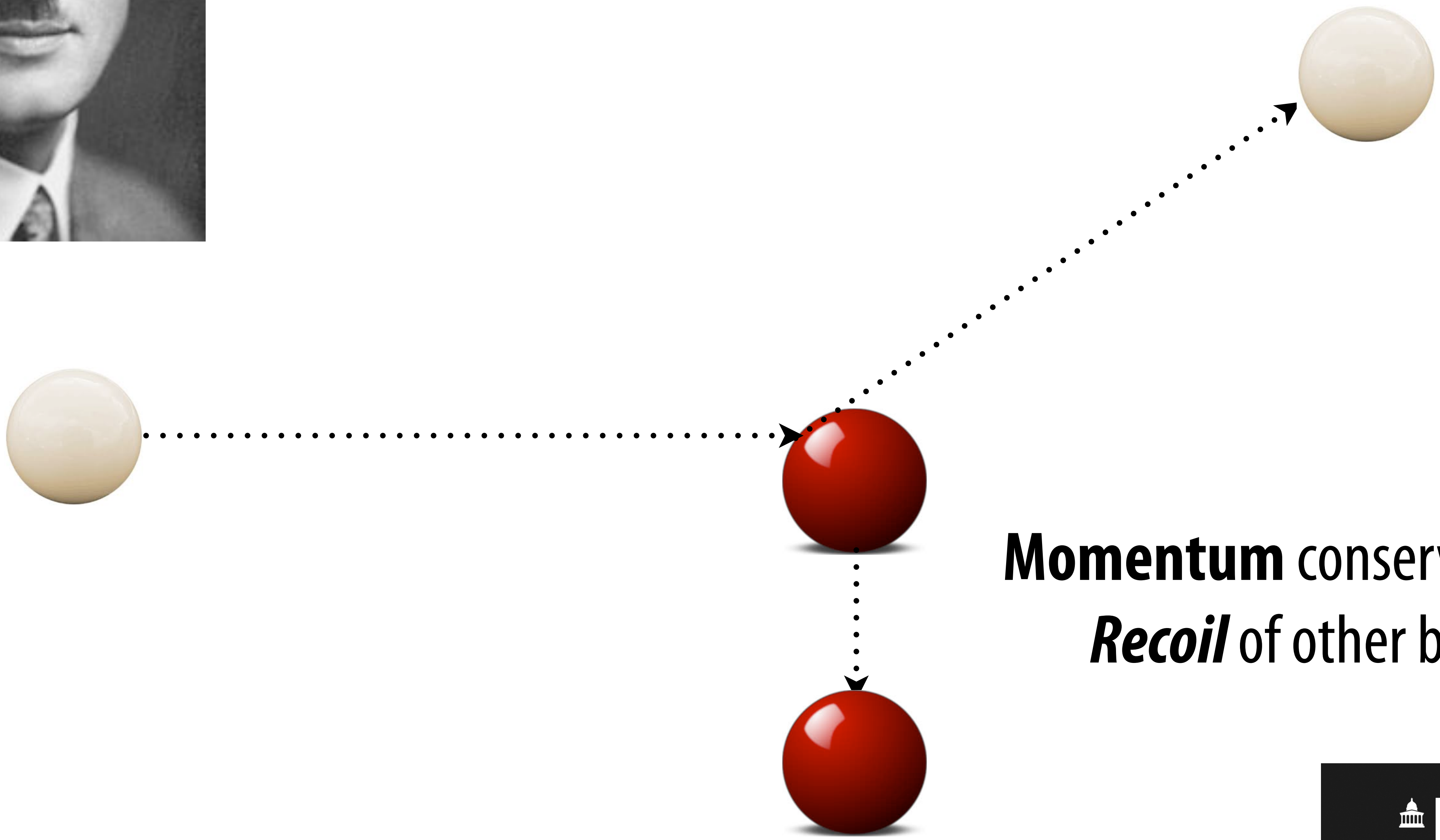

Momentum conservation:
Recoil of other ball

The Compton Effect

- ***1922 - Compton Scattering***
    - Elastic collision:
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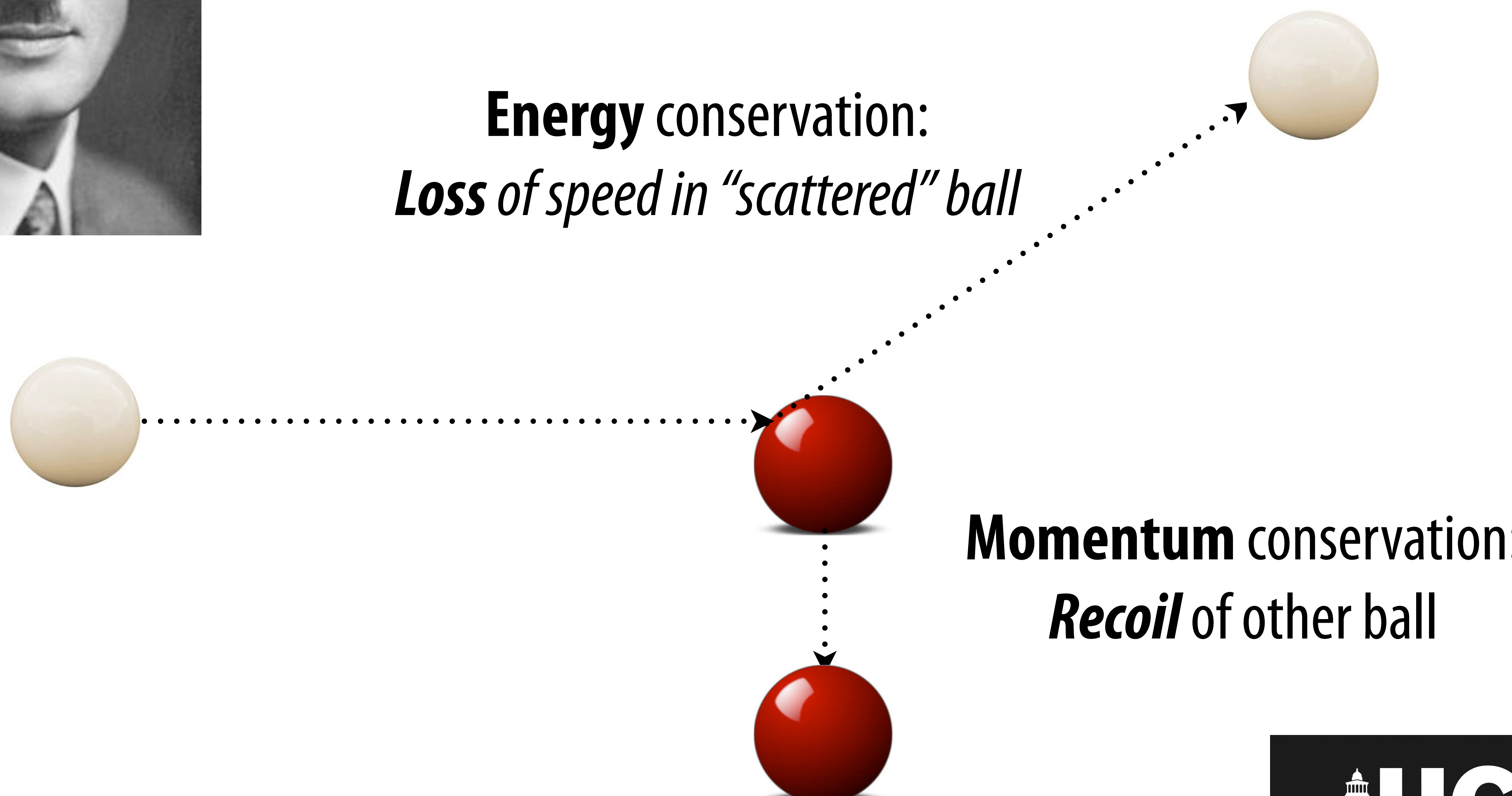


The Compton Effect

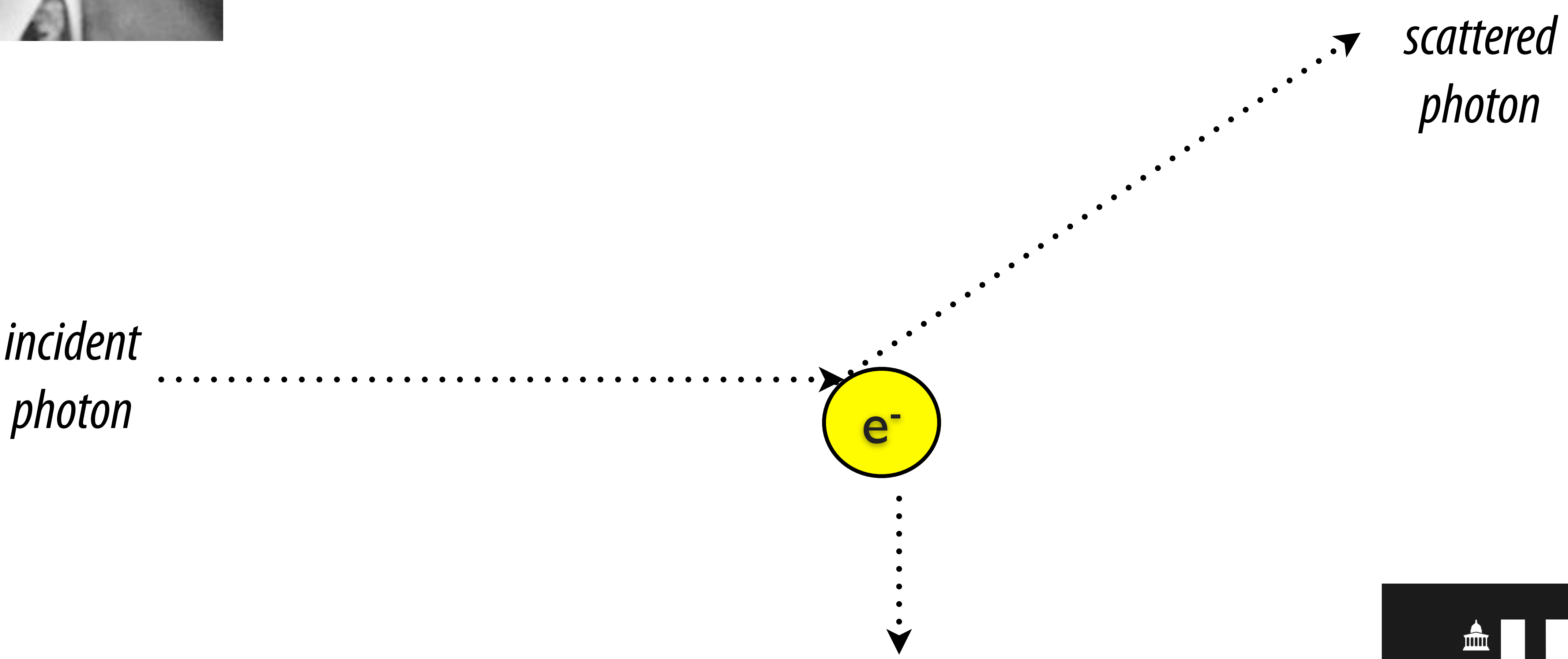
- ***1922 - Compton Scattering***
  - Compton's model:
  - Assume X-ray **photons** with energy and momentum following the **Planck-Einstein** formula:

$$E = hf \qquad\qquad p = \frac{h}{\lambda}$$

  - Treat collision elastically
    - **Momentum** and **energy** conserved.
  - and treat electron motion using **special relativity.**

The Compton Effect

- ***1922 - Compton Scattering***
    - Same basic physics as non-relativistic billiard balls.
    - (Relativistic calculation is actually easier! See Serway and Jewett, Chap 41)



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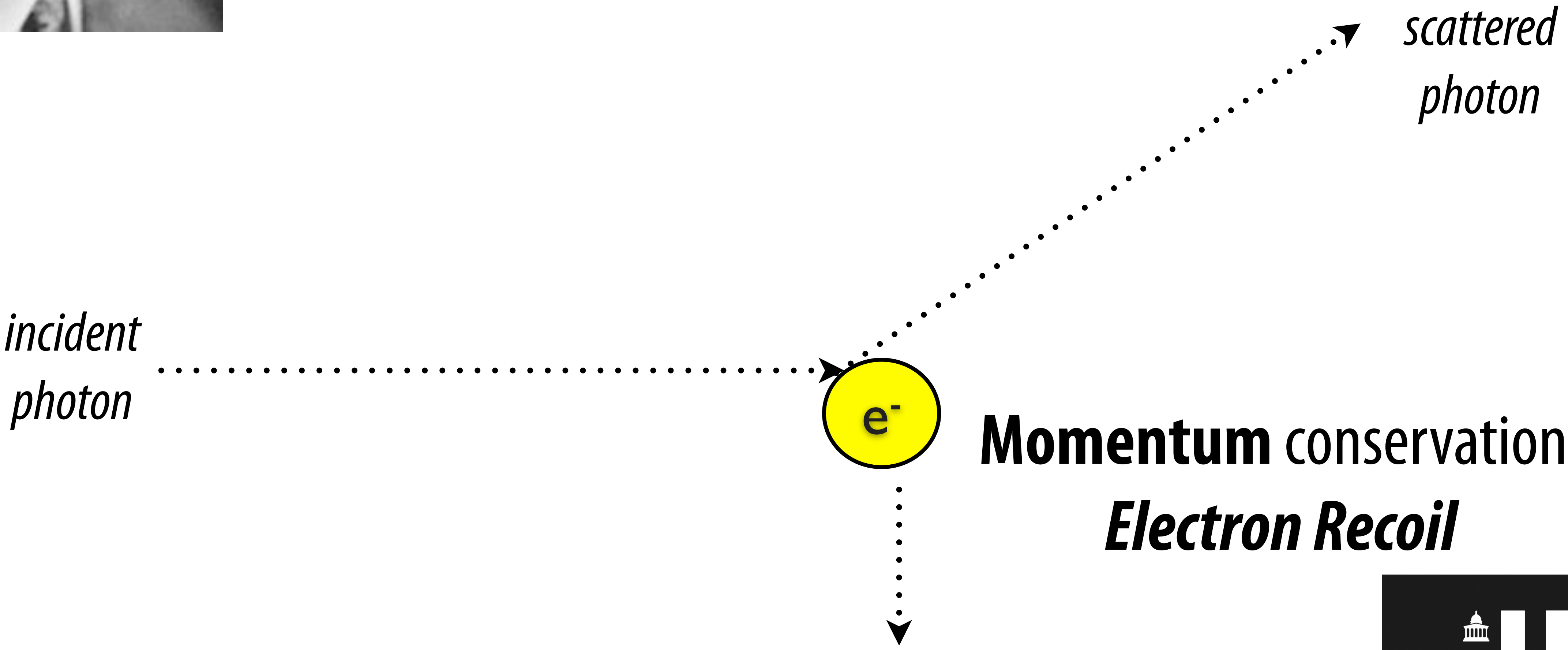

Momentum conservation:
Electron Recoil

The Compton Effect

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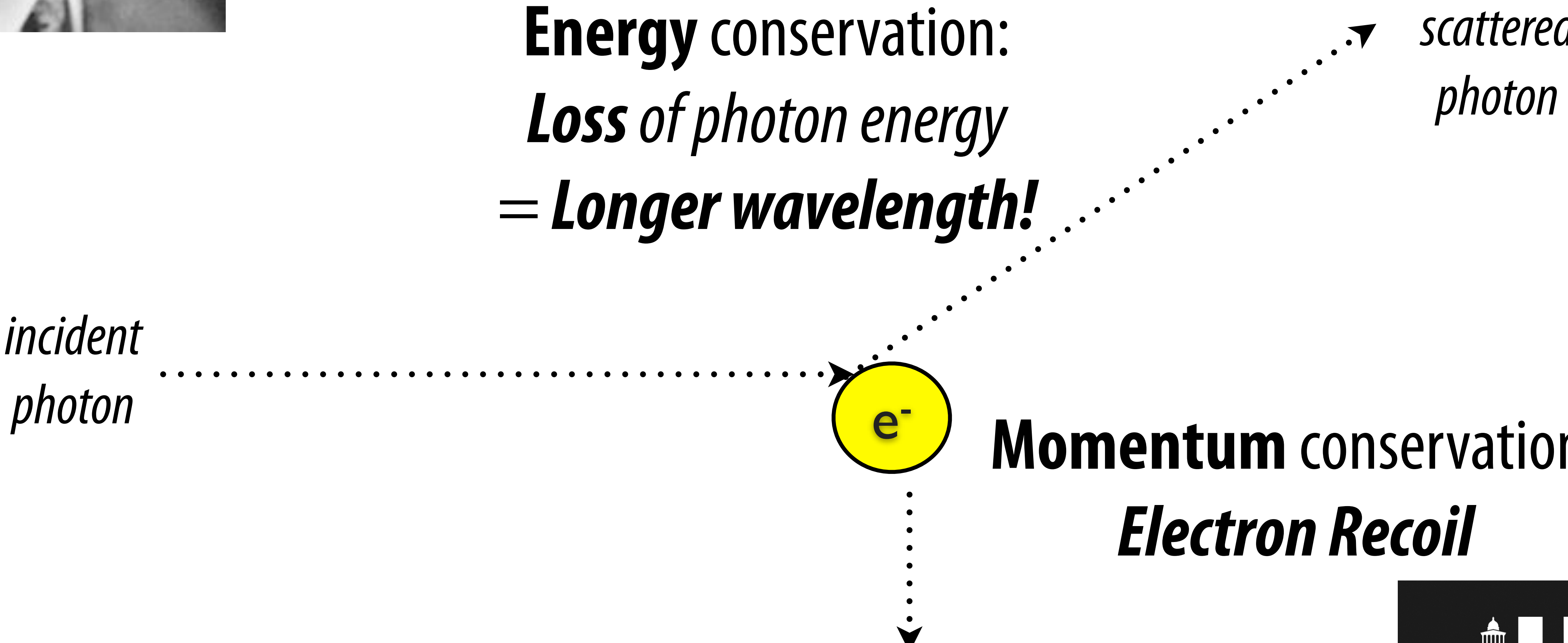
Energy conservation:
***Loss** of photon energy*
= ***Longer wavelength!***



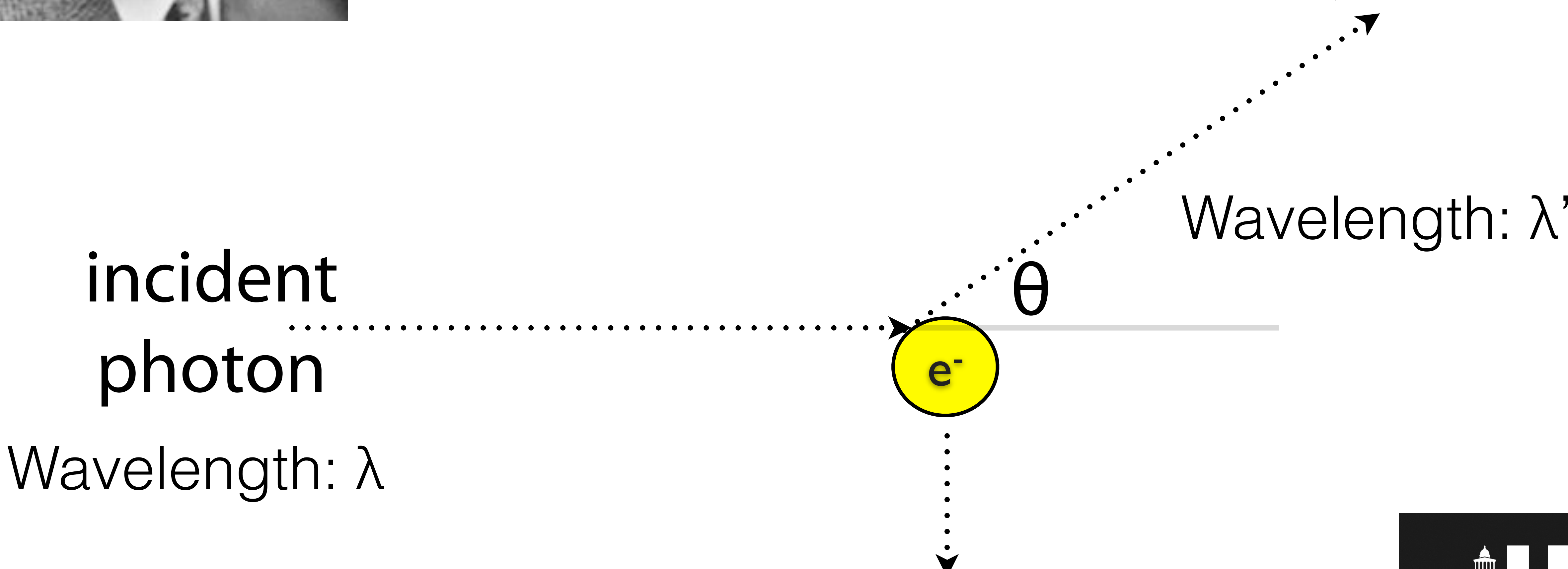
Momentum conservation:
Electron Recoil

The Compton Effect

- ***1922 - Compton Scattering***
  - Compton scattering formula:

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

  - where $\boldsymbol{m_e}$ is electron mass.
- **Wavelength shift** depends on **angle** only.



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- **Wavelength shift** depends on **angle** only.
- For an electron mass:

$$\frac{h}{m_e c} \approx 2 \times 10^{-12}\mathrm{m} = 2\mathrm{pm}$$

- Shift is only **measurable** when photon wavelength a few orders of magnitude above a picometre - e.g. x-rays (nanometre wavelength).

The Compton Effect

- *1922 - Compton Scattering*
  - Compton verified this wavelength shift **experimentally** scattering x-rays from a variety of different conductors.
  - In all cases, experiment closely **matched his theory** and **disagreed** with wave scattering!

From A.H. Compton, Physical Review 1923:

$$\lambda_\theta - \lambda_0 = 0.022 \text{ A} \quad \text{(experiment)}.$$

But according to the present theory (Eq. 5),

$$\lambda_\theta - \lambda_0 = 0.0484 \sin^2 45^\circ = 0.024 \text{ A} \quad \text{(theory)},$$

which is a very satisfactory agreement.

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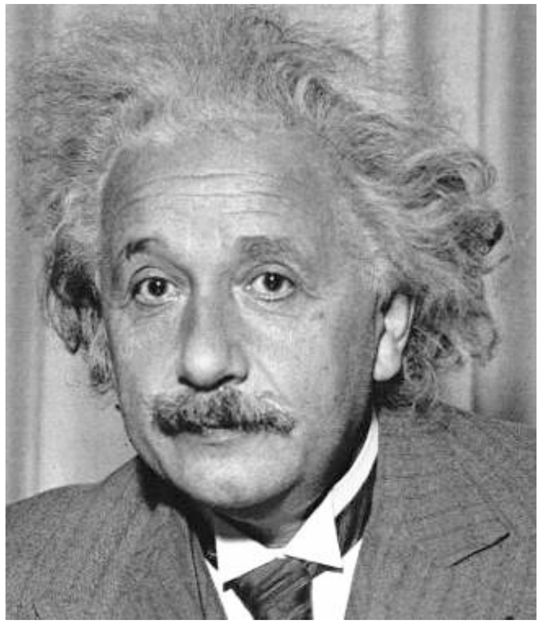
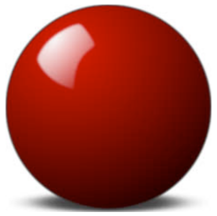
A particle and a wave?



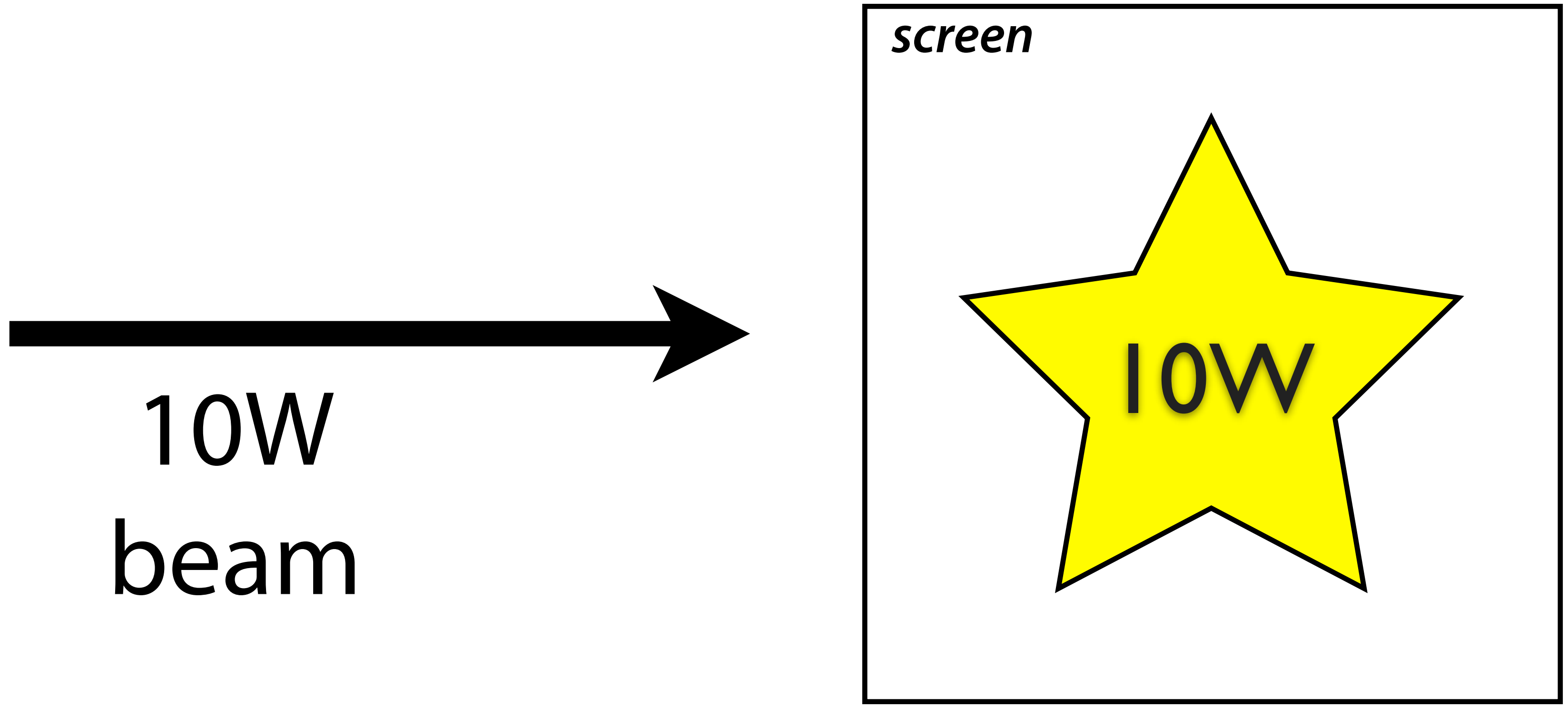
- Between them, Einstein's **photoelectric effect** argument and **Compton's scattering** experiments were unambiguous!
    - Light as a **particle** had to be taken seriously!
    - But **interferometry** experiments "proved" that light a **wave**.
- How could light be **both** a **particle** and a **wave**?
    - Answer: **Quantum Mechanics**

Wave-like and particle-like behaviour - the photon



Towards single photons

- What happens if we turn down the power of a laser?
- And keep on turning it down?



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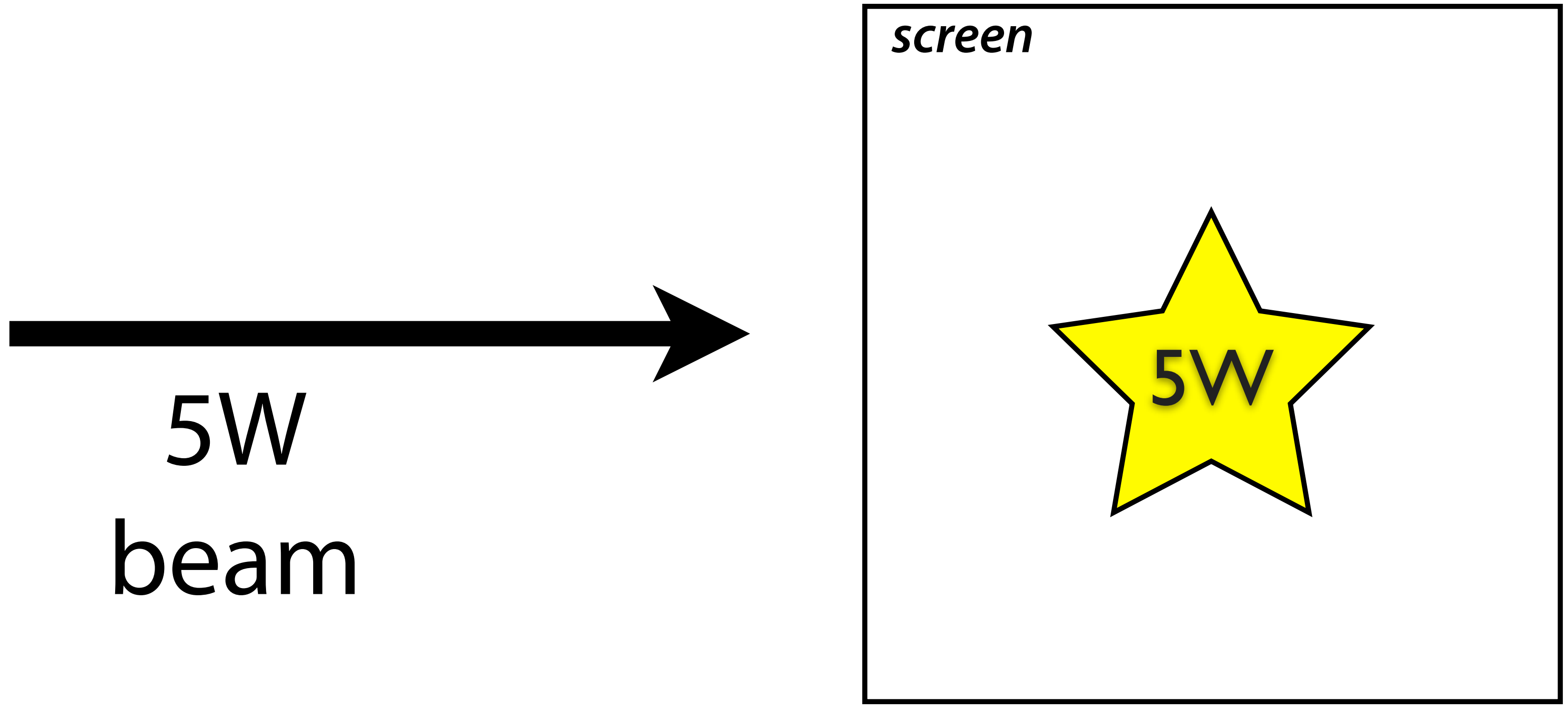

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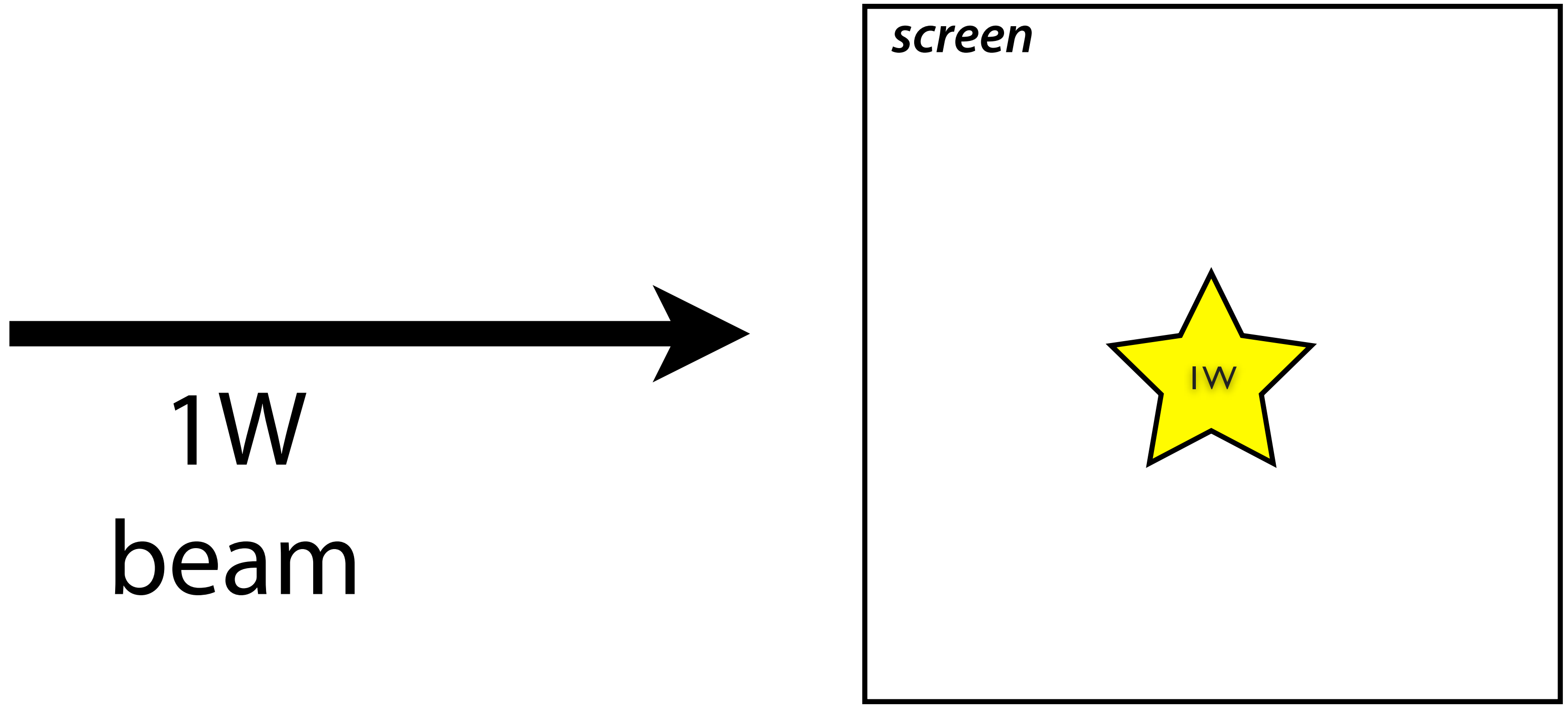

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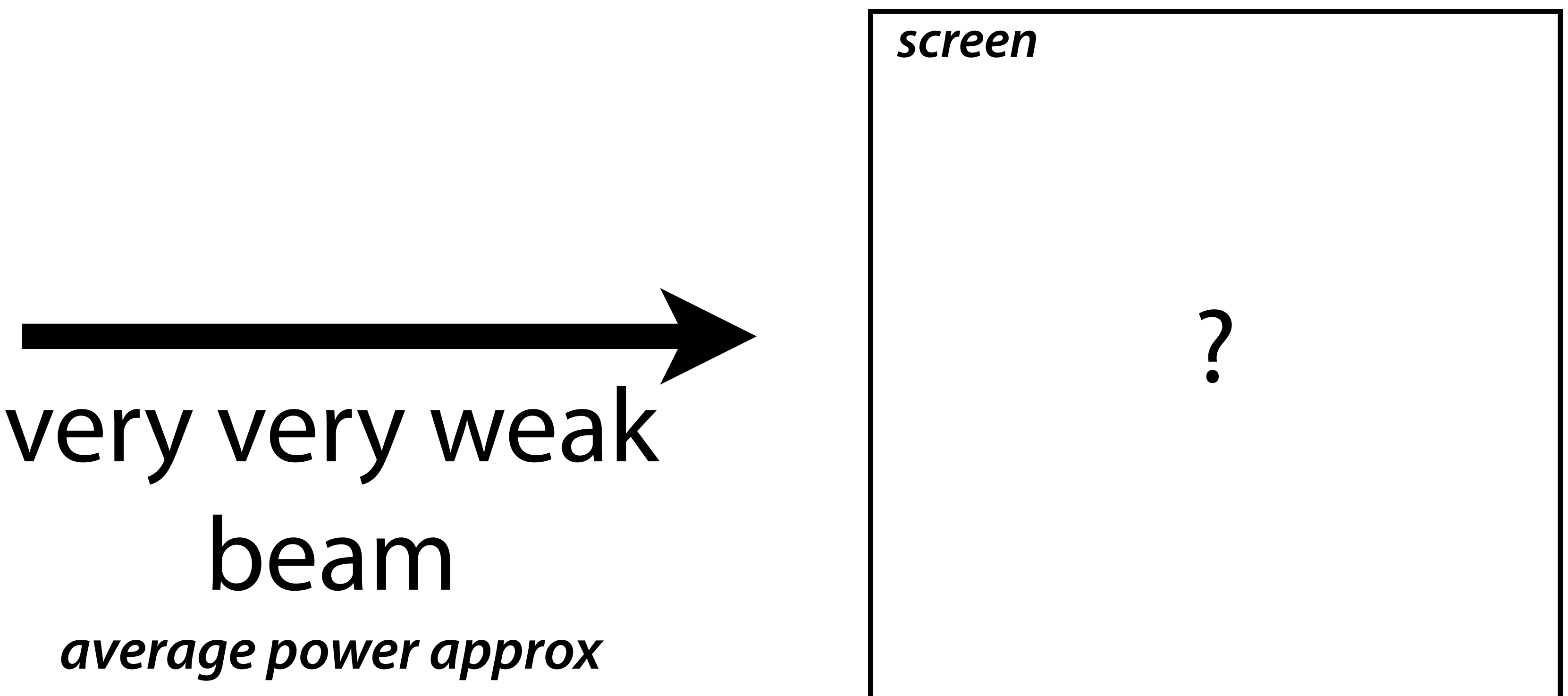

very very weak beam

average power approx

$hf = \hbar\omega$

(one photon per second)

Freq. of a yellow photon: $f \approx 5\text{x}10^{14}\ s^{-1}$
Energy of a yellow photon: $hf \approx 3\text{x}10^{-19}$ J

Towards single photons

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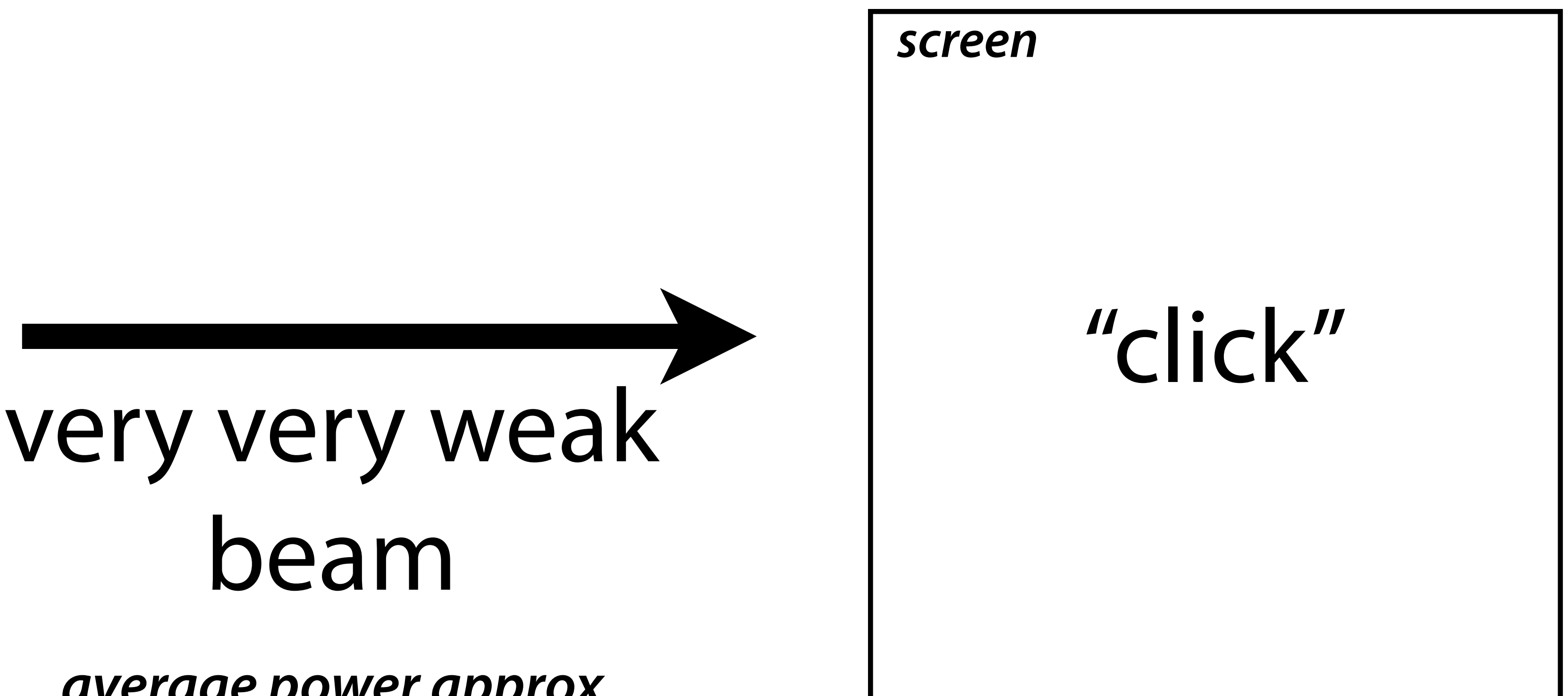

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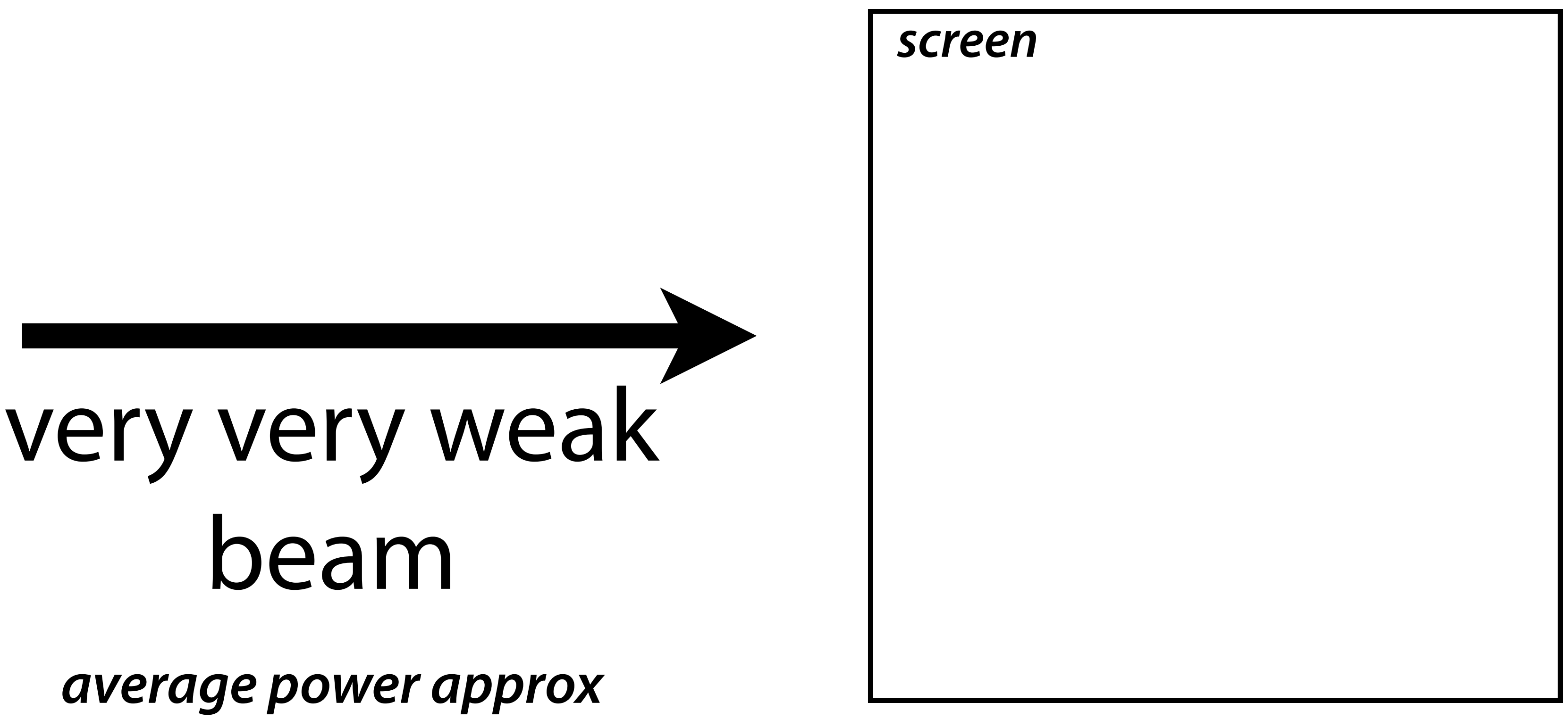

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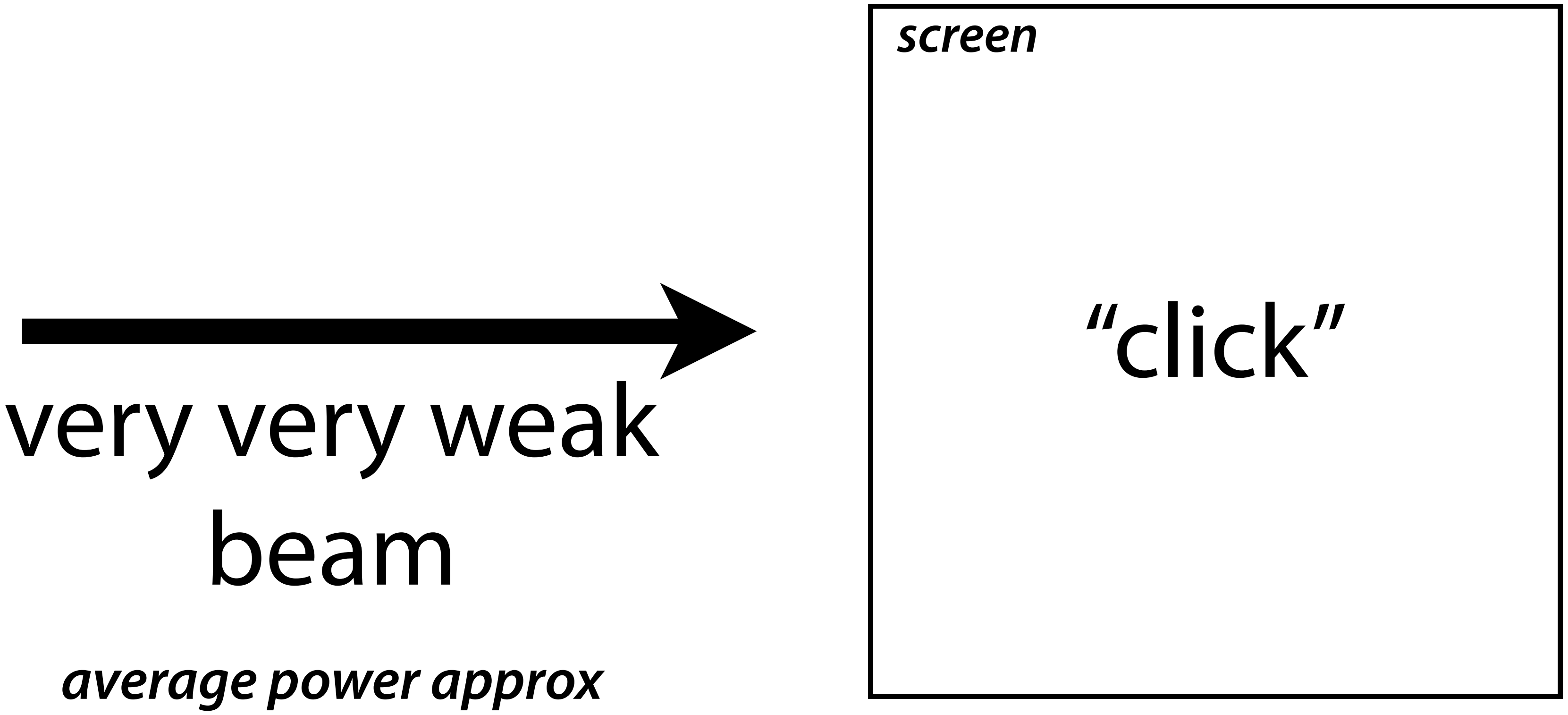

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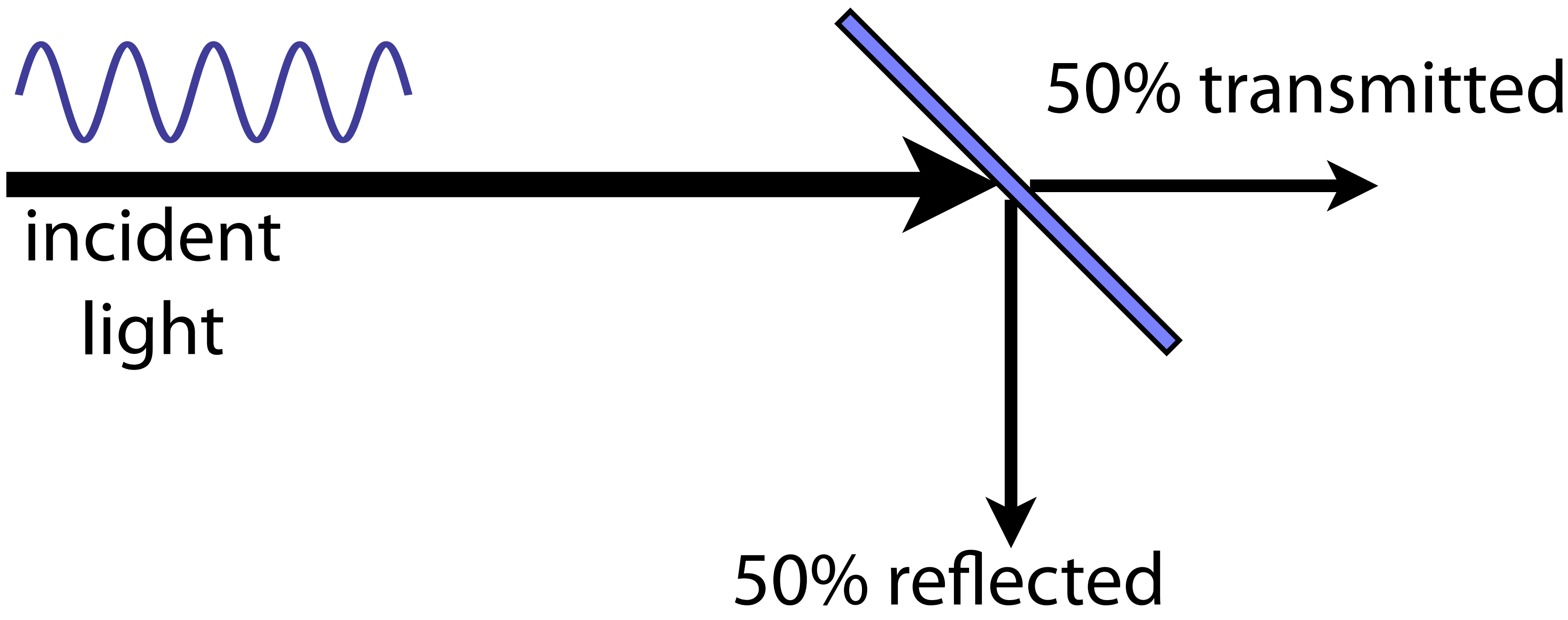
- Detection no longer continuous.
- Detector "clicks" at random intervals, on average once per second.

Photons on a beam splitter

- Recall the beam splitter
  - ***50% light transmitted***
  - ***50% light reflected***



Photons on a beam splitter

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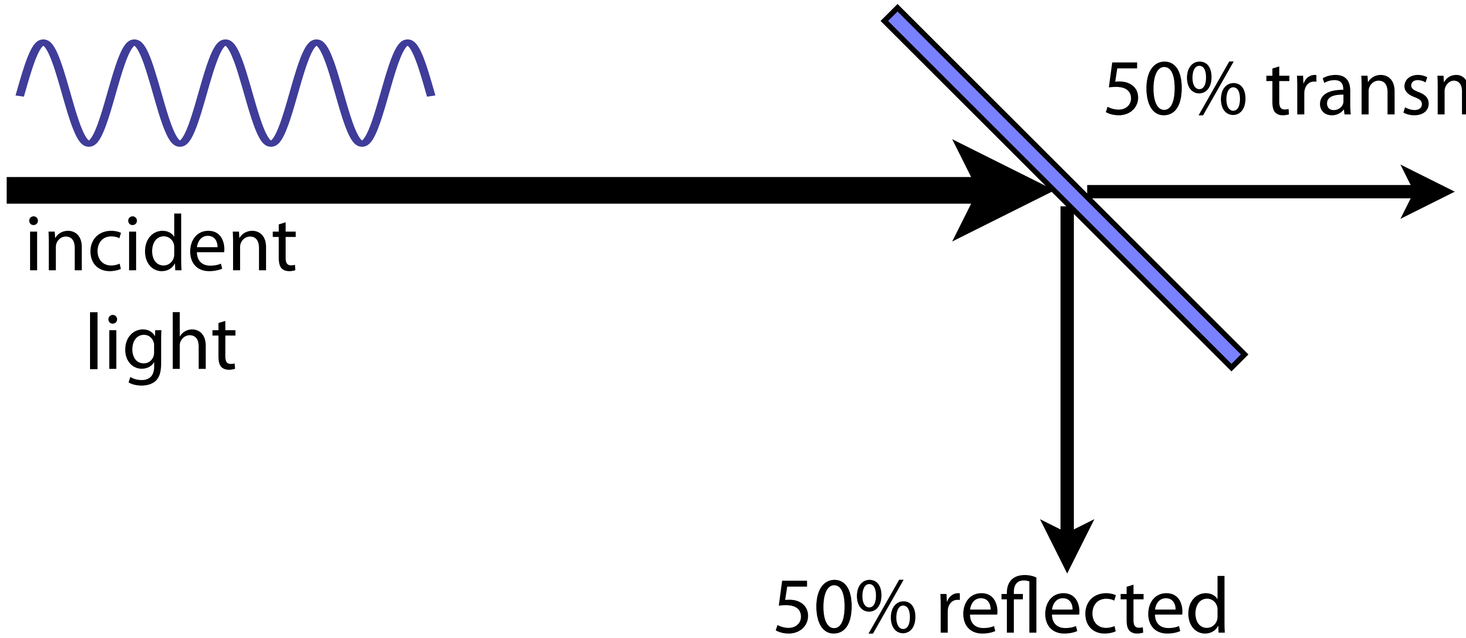
  - ***50% intensity transmitted***
  - ***50% intensity reflected***



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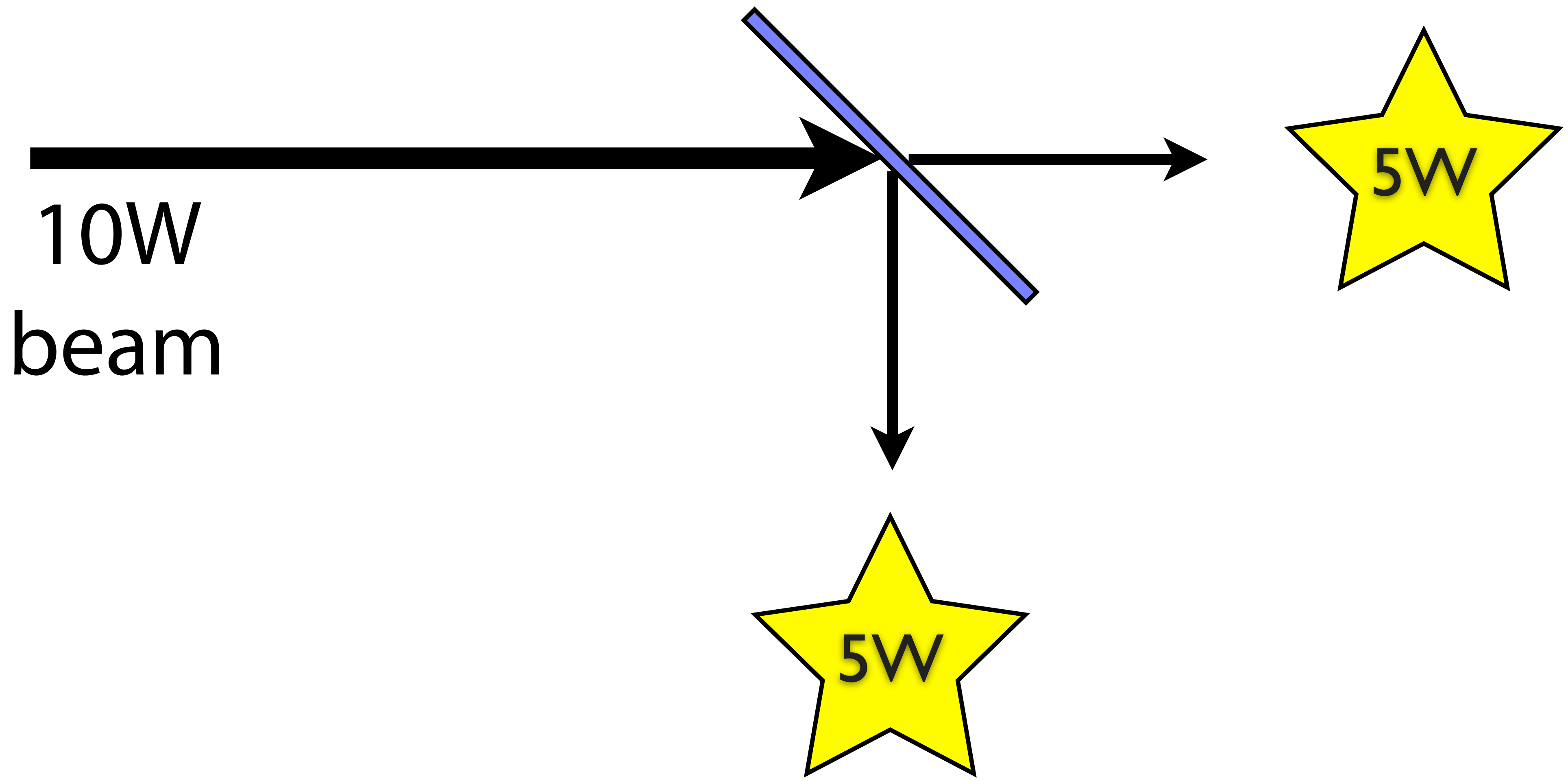

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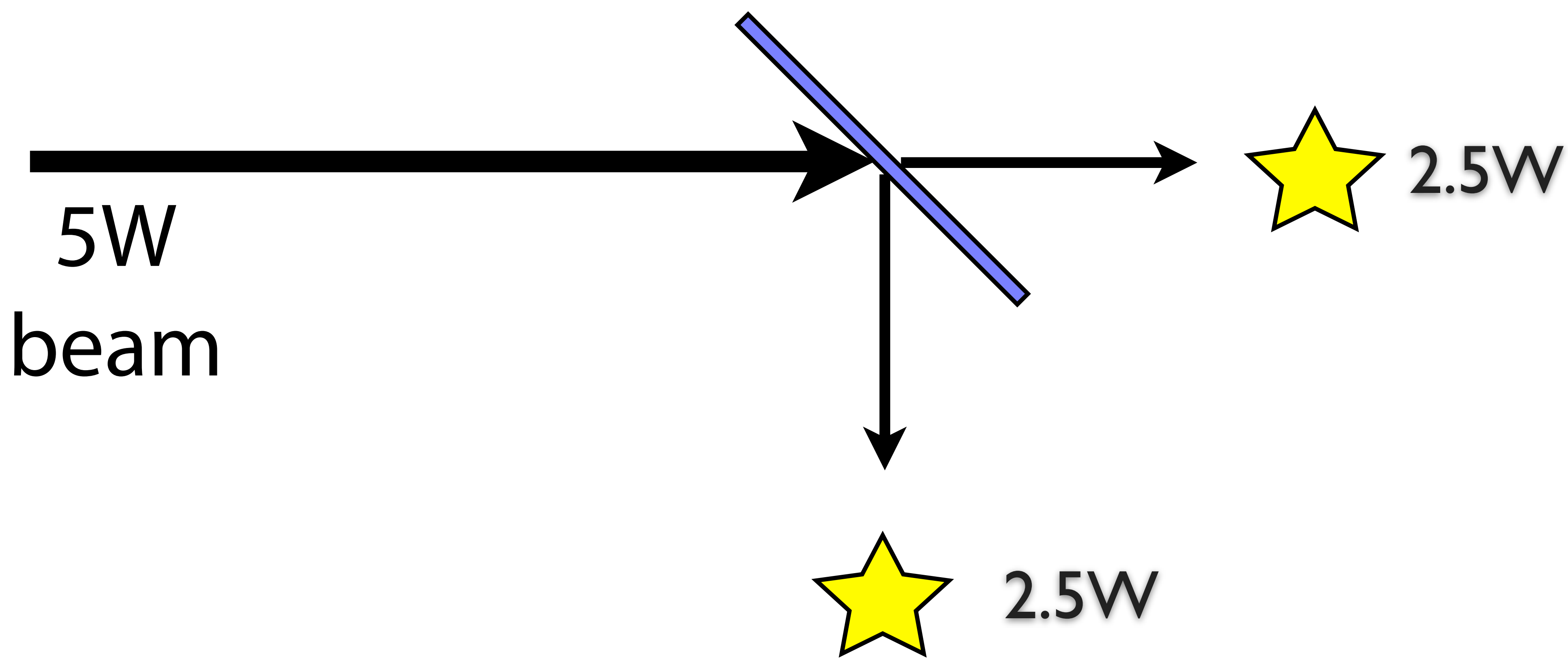

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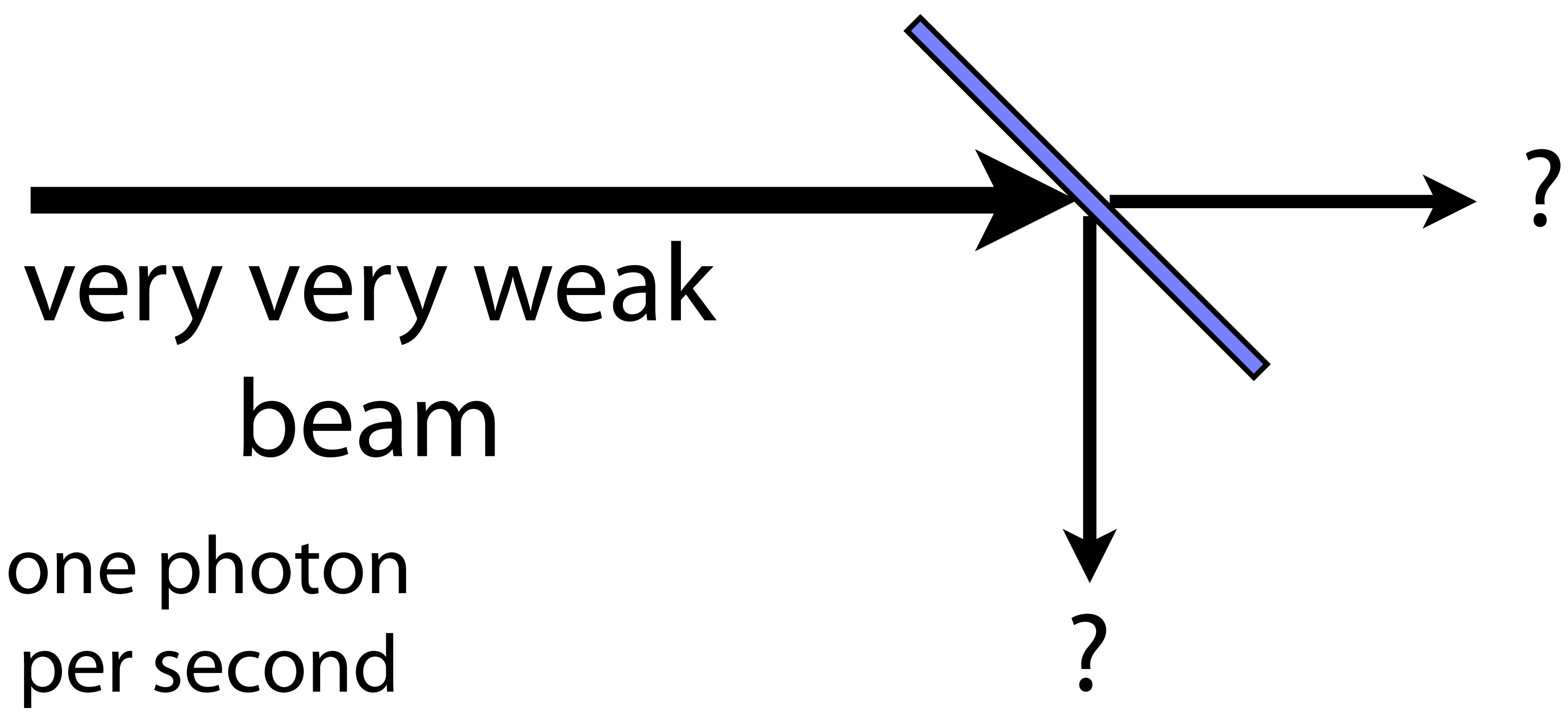
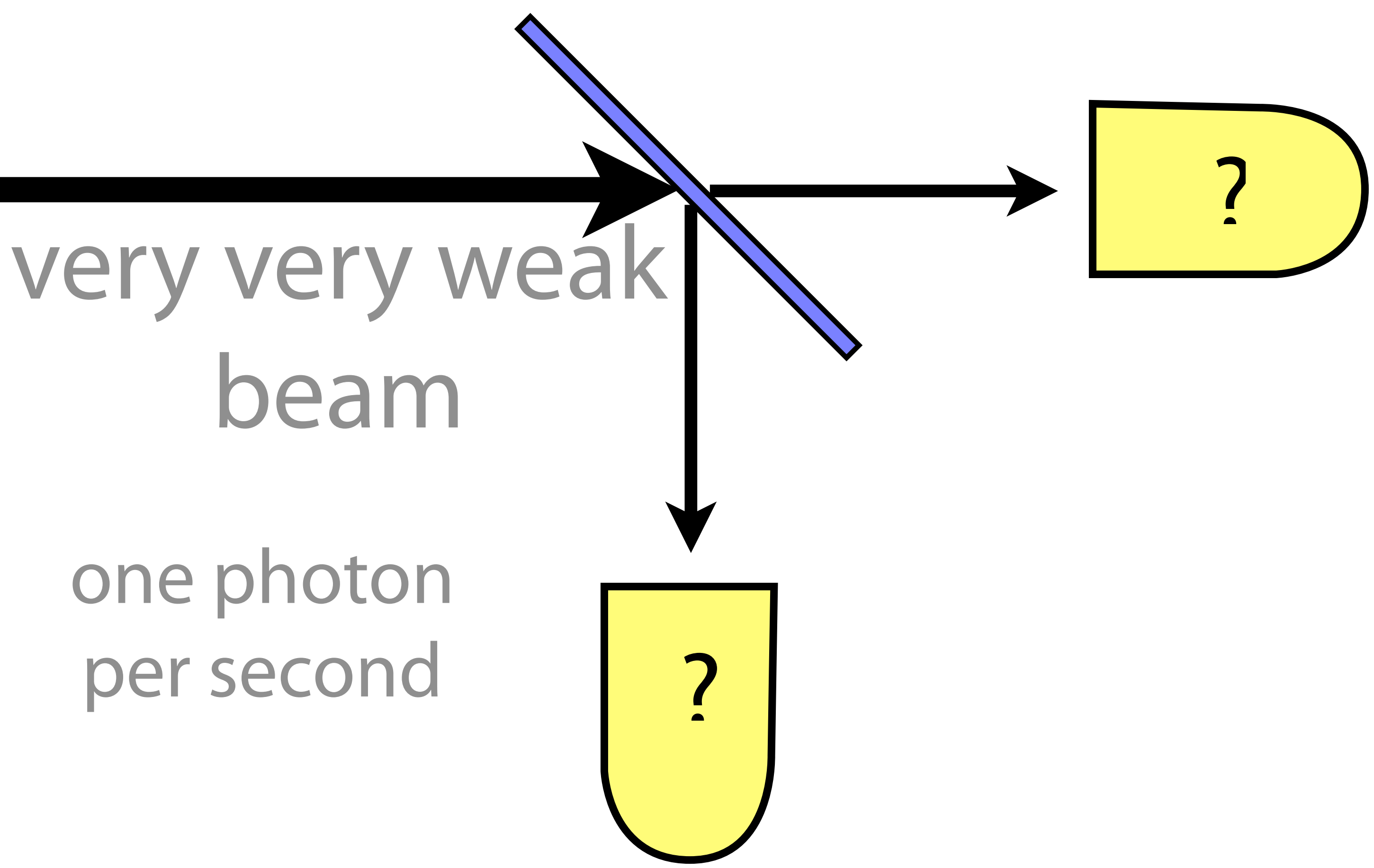


Quiz

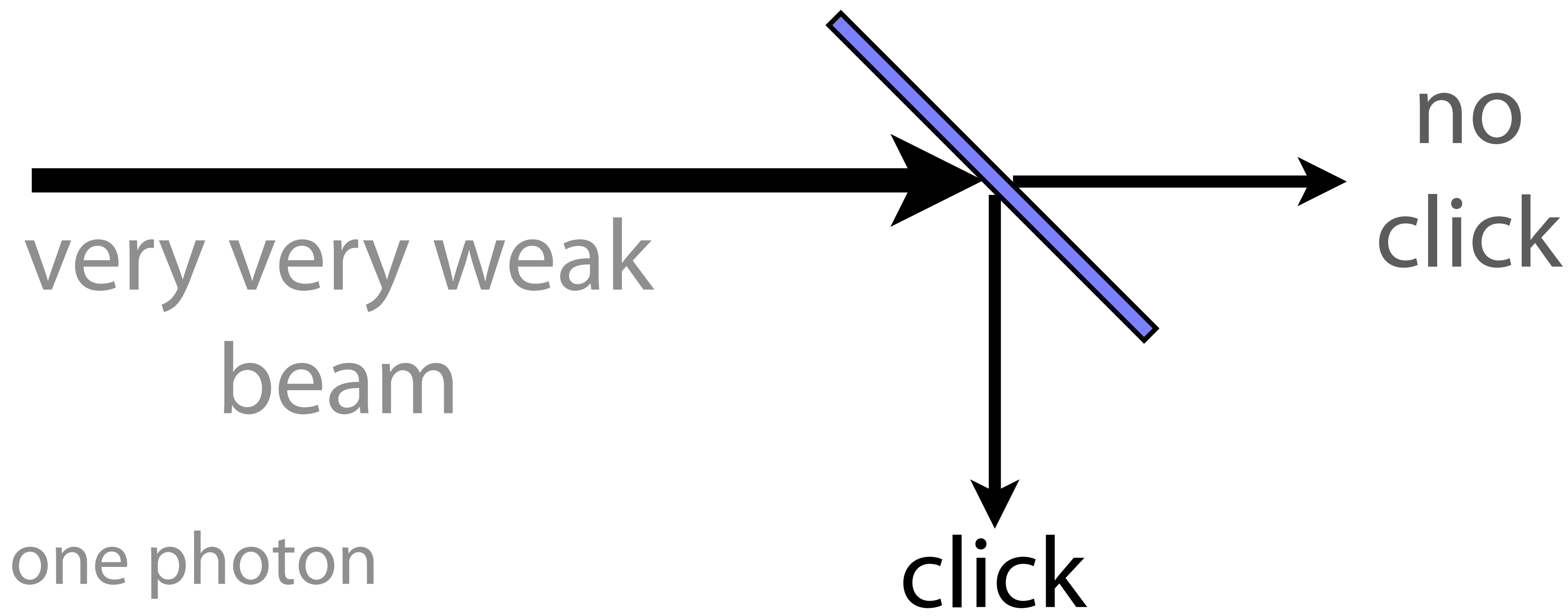


- ***What will we see?***
  - 1. Clicks always come in **pairs**.
  - 2. **Only one** detector clicks, and always the **same** detector.
  - 3. Only one detector clicks, and which detector clicks is **random**.

Photons on a beam splitter

- Single photons **cannot be divided.**
- **Half** of the photons are detected in one beam and **half** in the other.
- The probabilities of each case (50:50) are reminiscent of the intensities of a strong classical beam.

With 50% probability we see:



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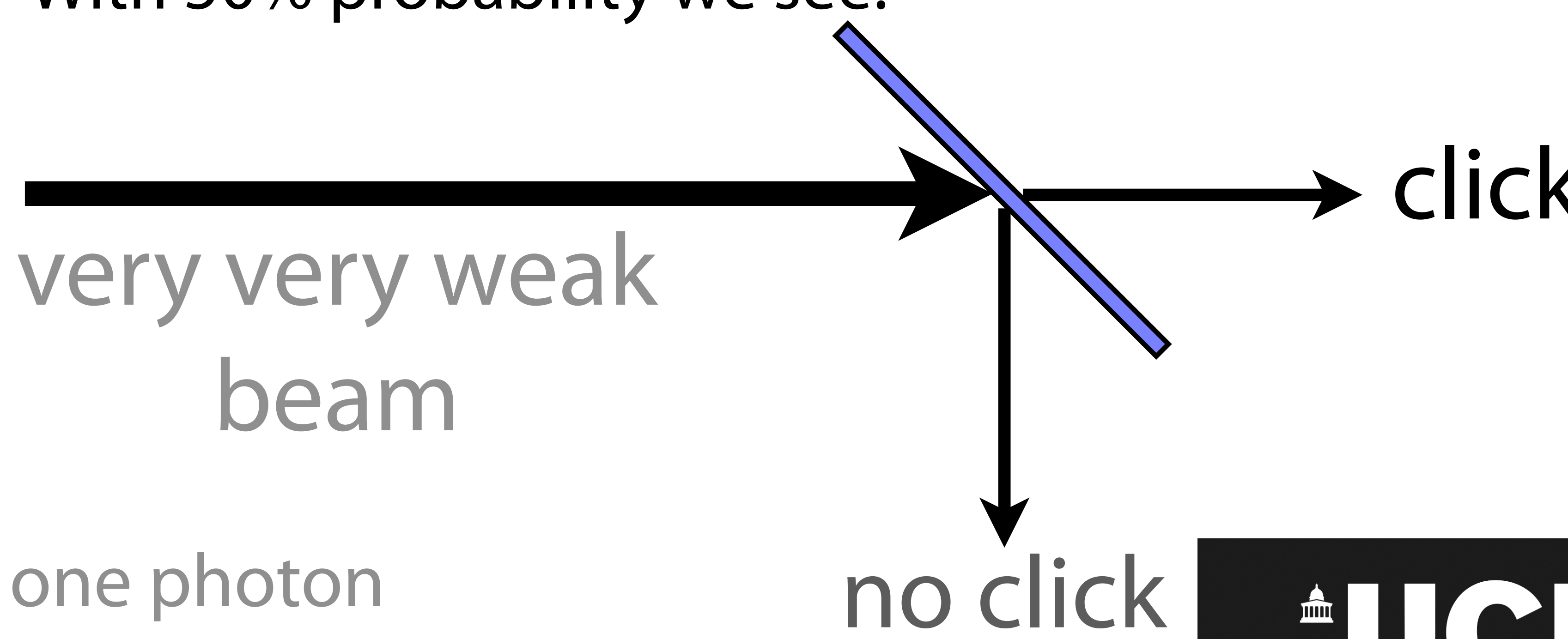
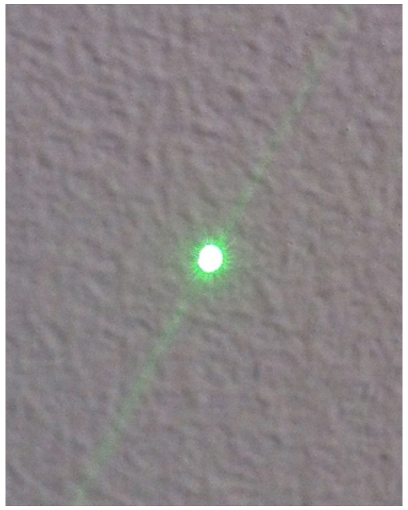


Classical limit and Quantum limit

1 photon "click"

10^{15} photons / sec



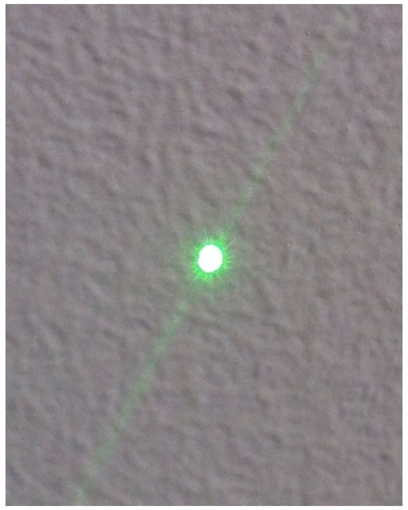
- **Quantum Limit**
  - Small numbers of photons
  - Quantum behaviour dominates
  - Quantum mechanics **essential**
- **Classical Limit**
  - Very large numbers of photons
  - Quantum behaviour "averages away"
  - Classical physics a **very good approximation**.

Classical limit and Quantum limit

1 photon

"click"

10^{15} photons / sec

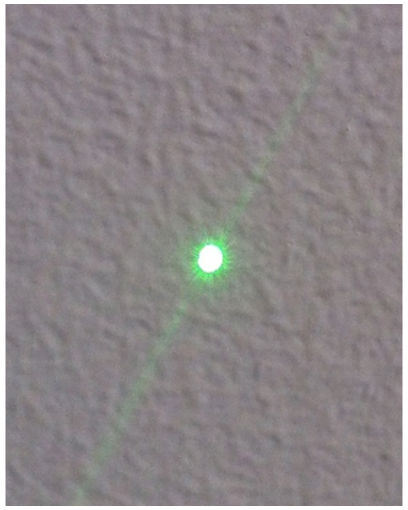


- **Quantum** and **classical physics** should (often but not always) be consistent.
- **Classical physics** works very well for most physical situations at "large" scales.
- So if often if we consider **average behaviour** of **large numbers** of quantum particles, we should recover classical behaviour.
- ***But not always: Exceptions will be*** phenomena not well described by classical physics
    - E.g. **Black-body radiation**
    - **photo-electric effect**.

Classical limit and Quantum limit

1 photon "click"

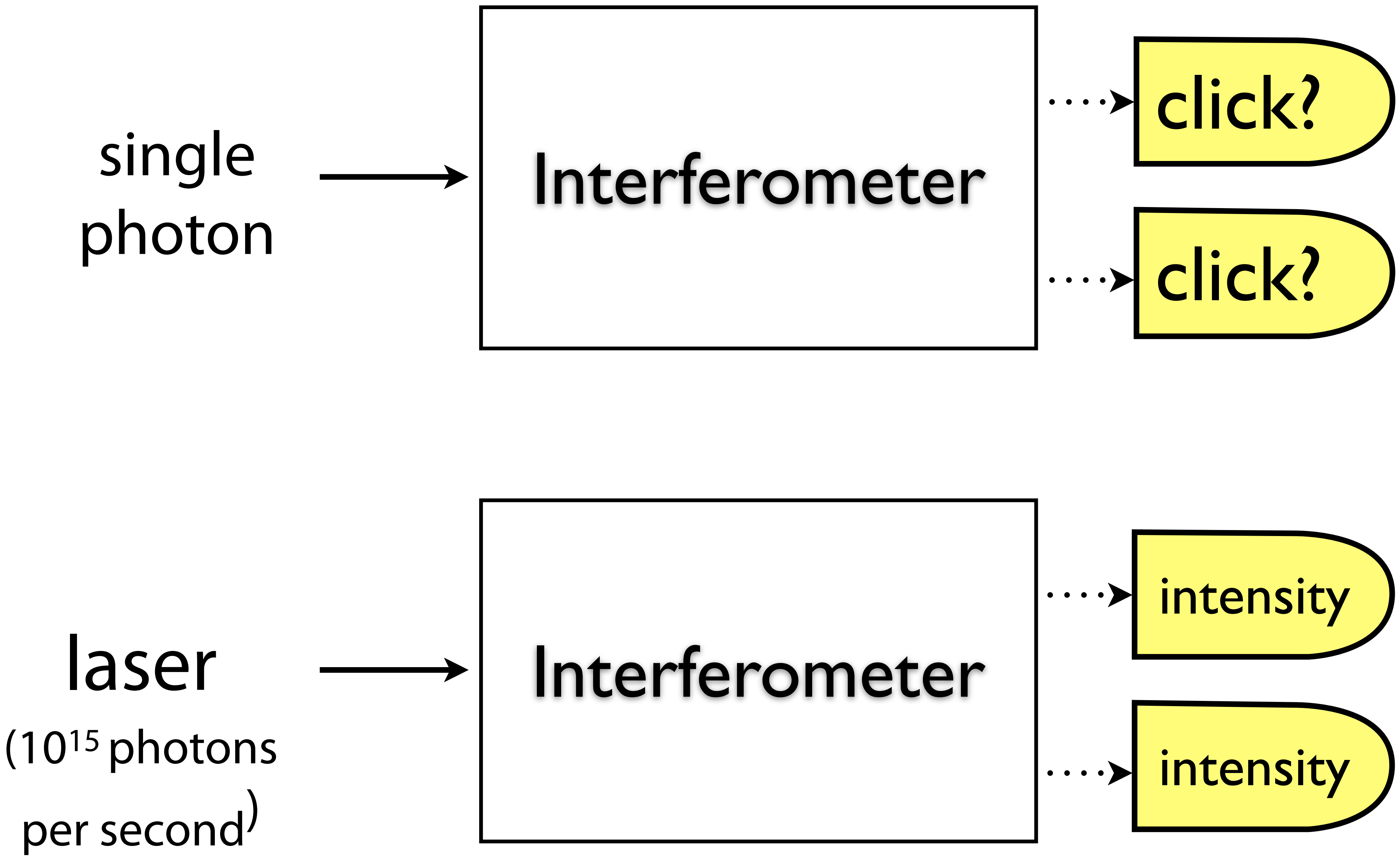
10^{15} photons / sec



- But single photon behaviour is a good example of this.
- If we take **large numbers** of photons, we'll no longer see the "granularity" of individual photons.
    - E.g. can you tell the difference between **10^{15} photons** and **10^{15} -1** photons?
- Classical physics reproduces the **average behaviour** of single photons in this case.

Single photon vs laser

- Consider two almost identical interference experiments.



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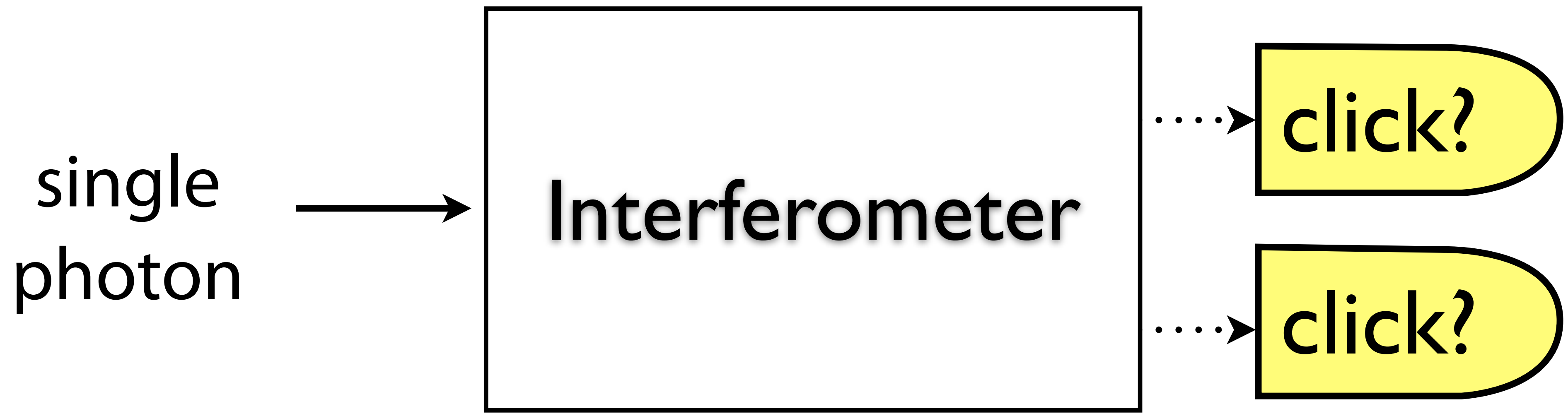
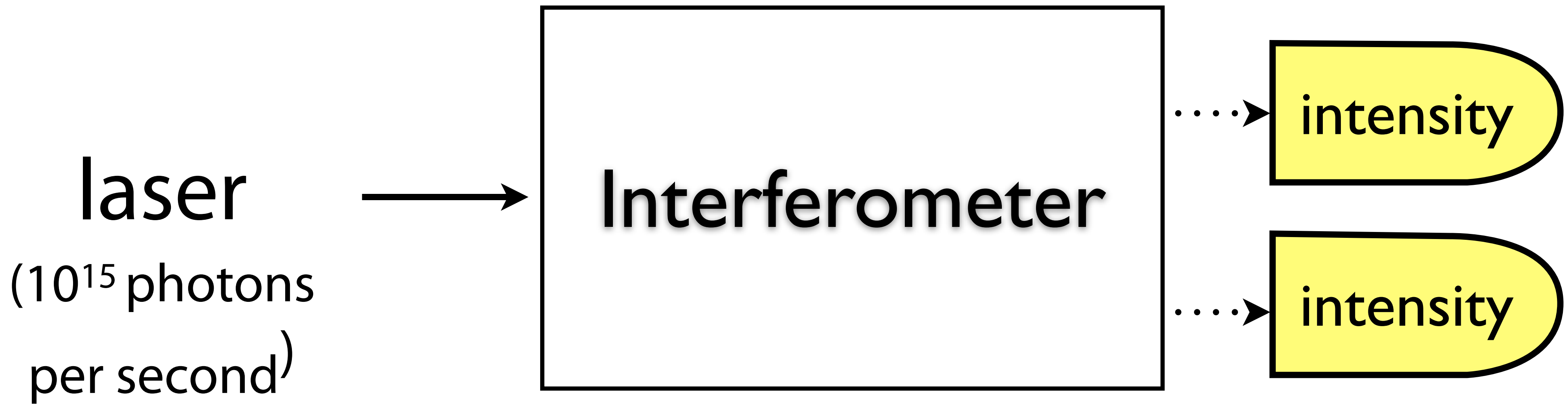


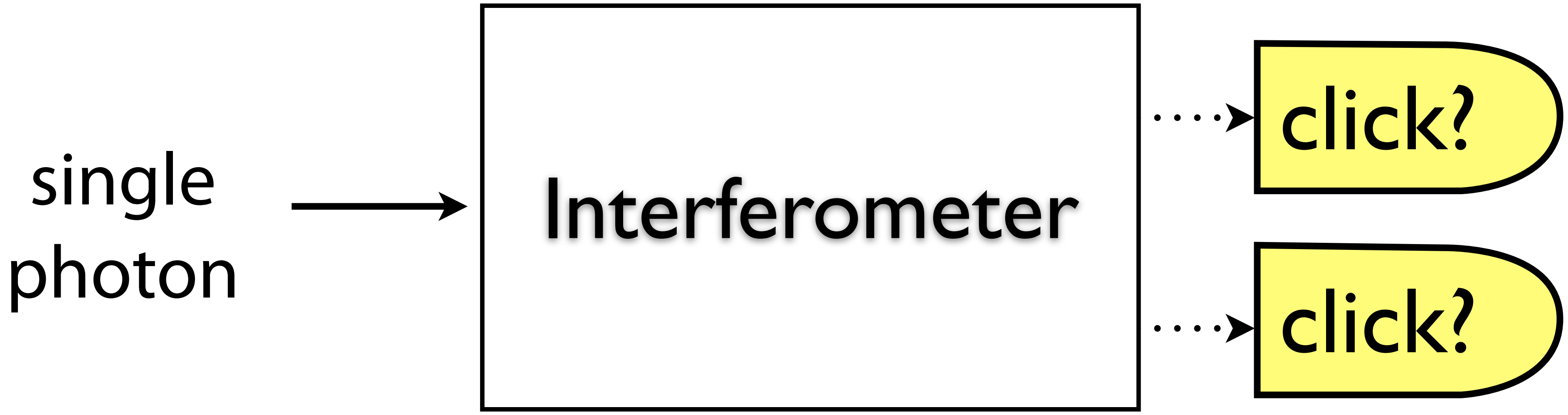
Classical Limit



Single photon vs laser

- The classical experiment, can be thought of as 10^{15} repetitions of the quantum experiment.

Quantum Limit

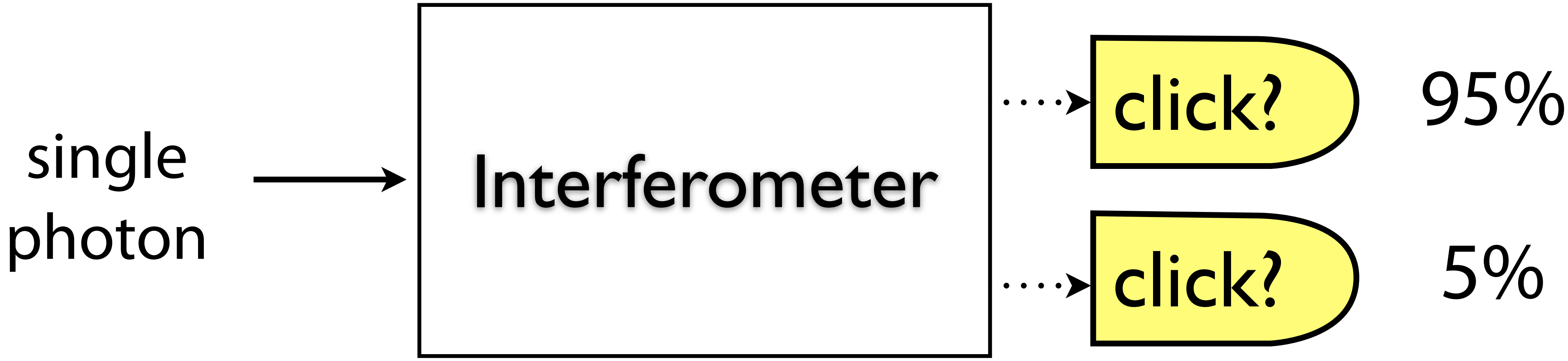


Classical Limit

Quiz

- If, after repeating the single photon experiment we observe the following probabilities of clicks in the detectors:

Quantum Limit



- What will be the intensities observed in the same experiment with a 10W laser?
    - 1. Top: 5 W Bottom: 5 W
    - 2. Top: 9.5 W, Bottom: 0.5W
    - 3. Something else

Quiz

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    - 1. Top: 5 W Bottom: 5 W
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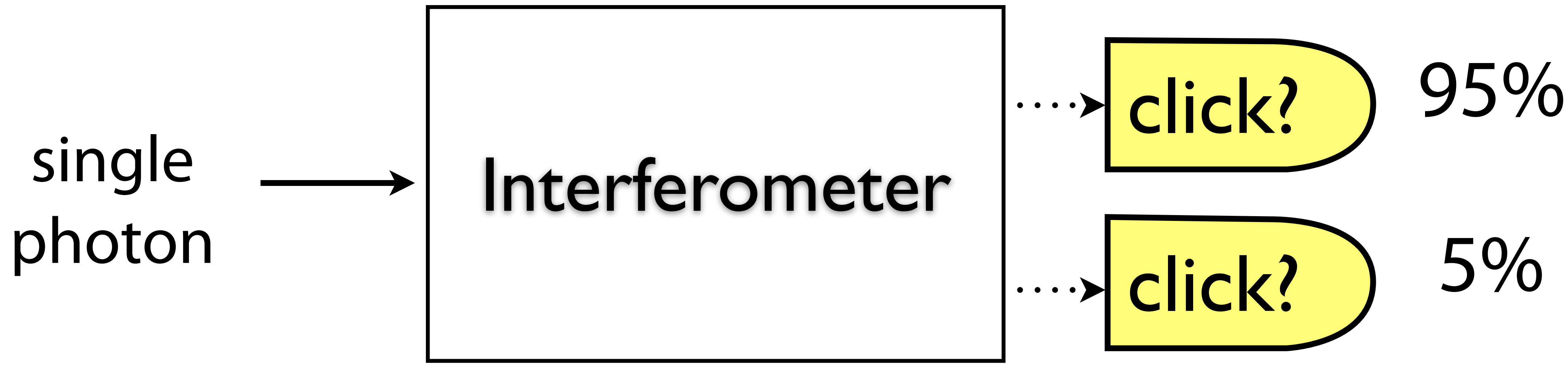
Single photon probability rule

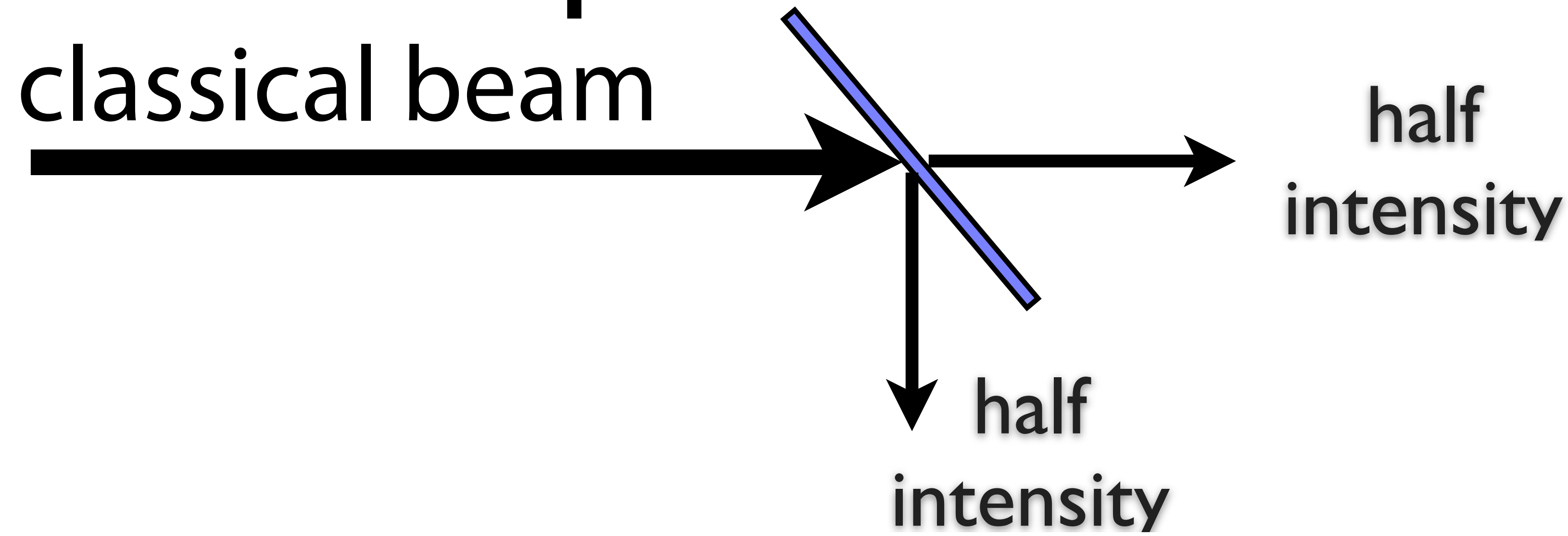
- In general, in the intensities in the classical experiment are proportionate to probabilities in the equivalent single photon expeiment.

Quantum Limit

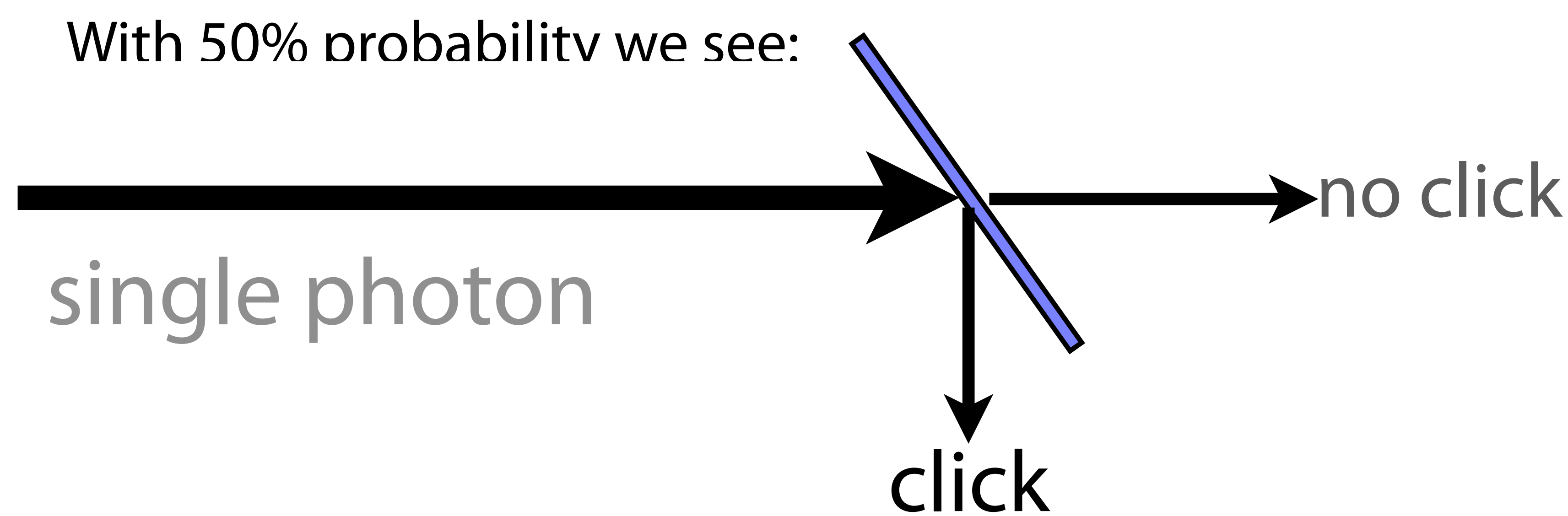


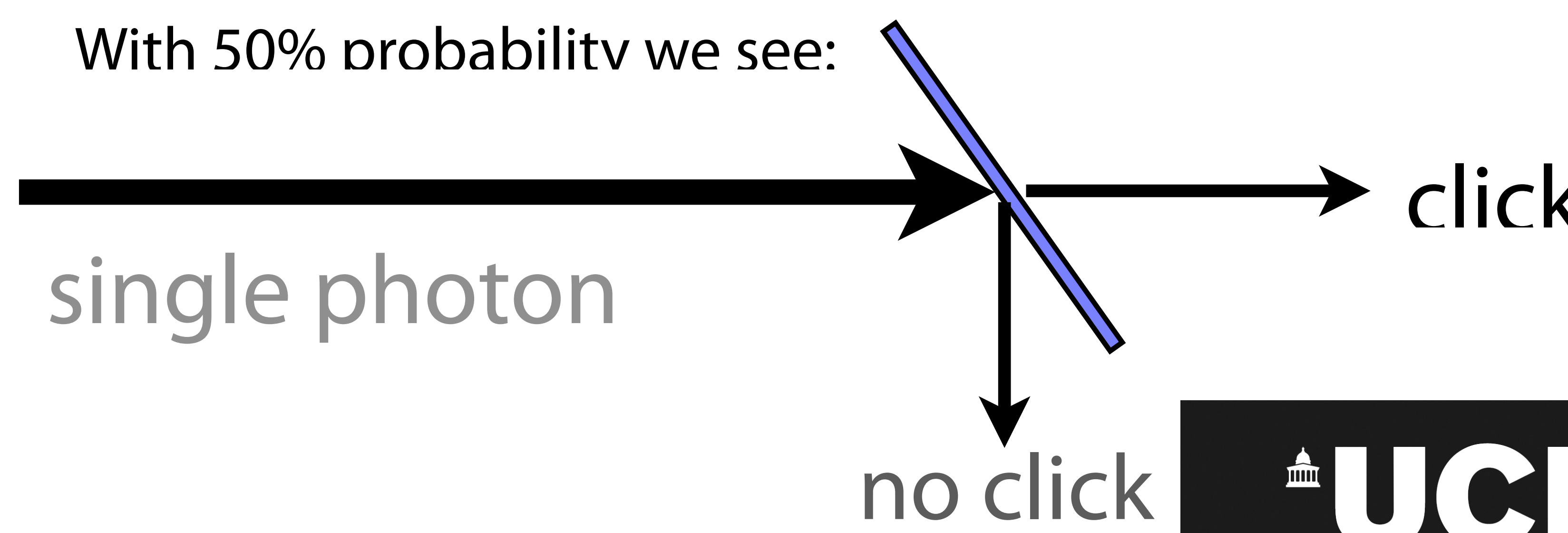
Classical Limit

Probability rule examples



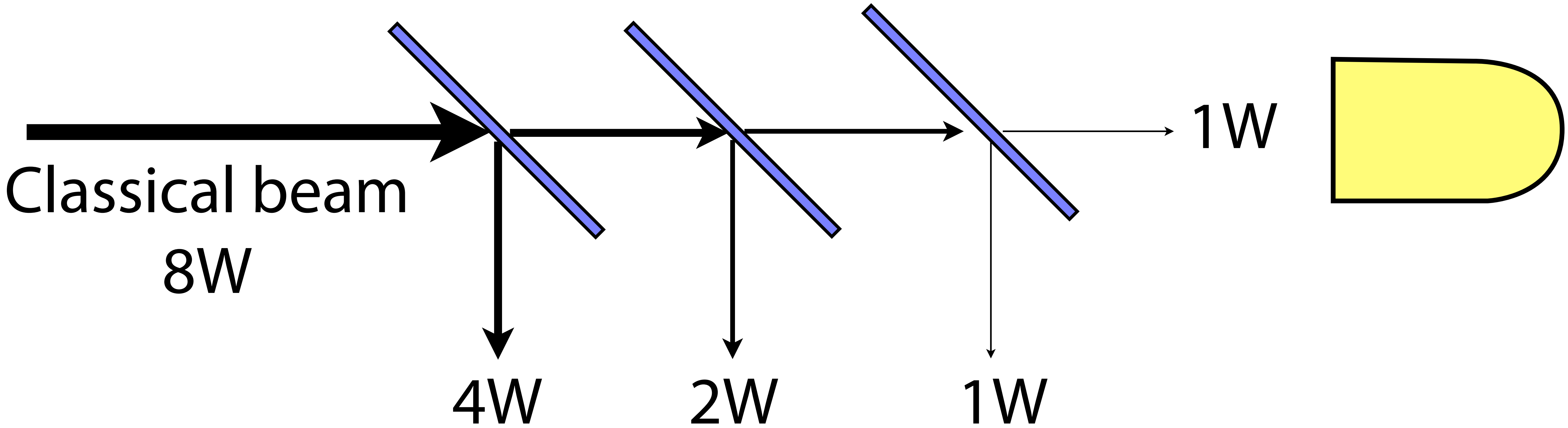
- Using this probability rule, we can look again at a single photon on a beam splitter.
- Classical intensity is split **50:50**.
- Photon can only click in 1 detector.
- Hence there must be a 50% probability for a click in each detector.





UCL

Quiz

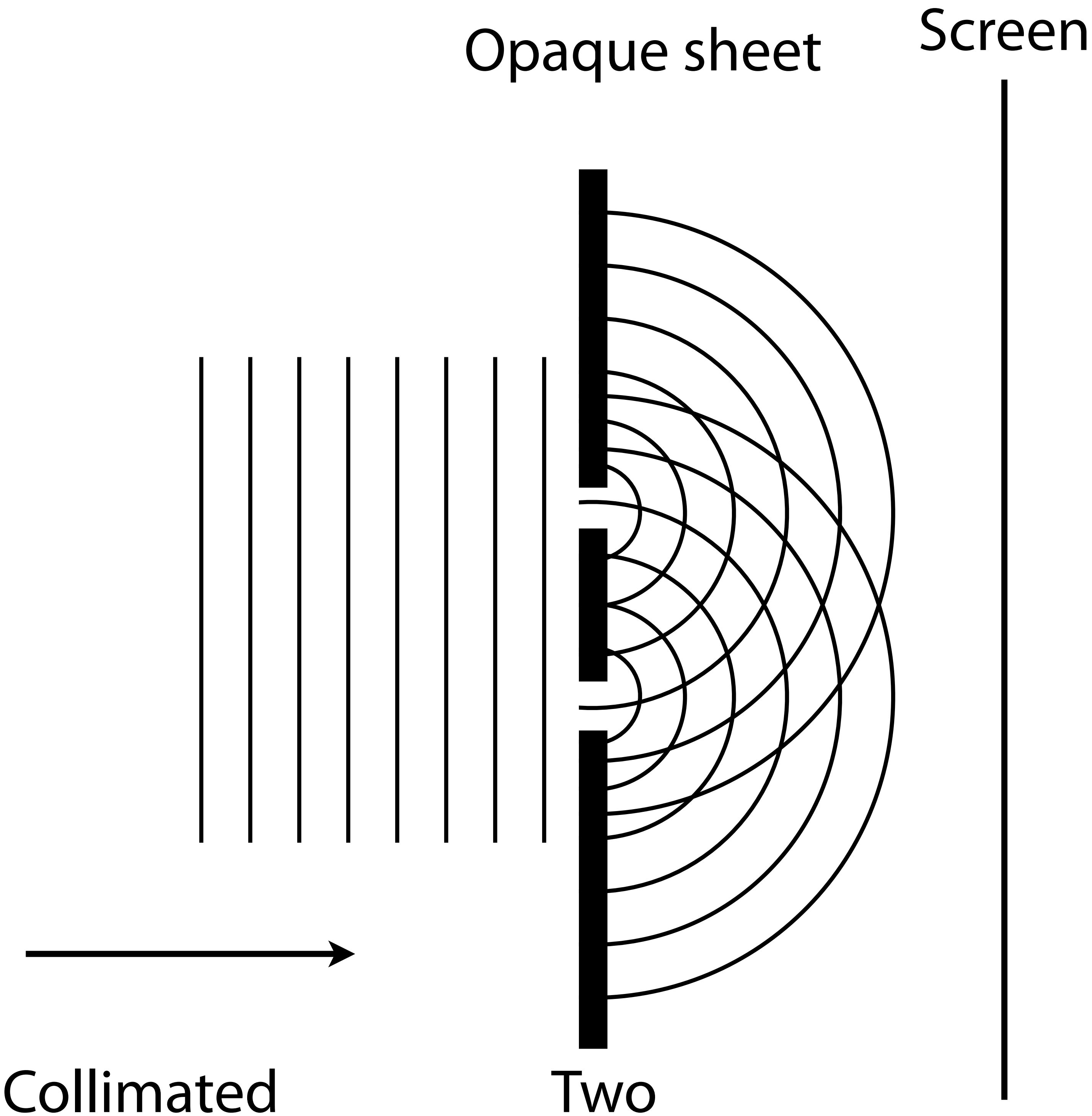


- If we repeat this experiment with a single photon, what is the **probability** that the photon **clicks** in the “**yellow detector**”.
  - 1. 100%
  - 2. 50%
  - 3. 25%
  - 4. 12.5%

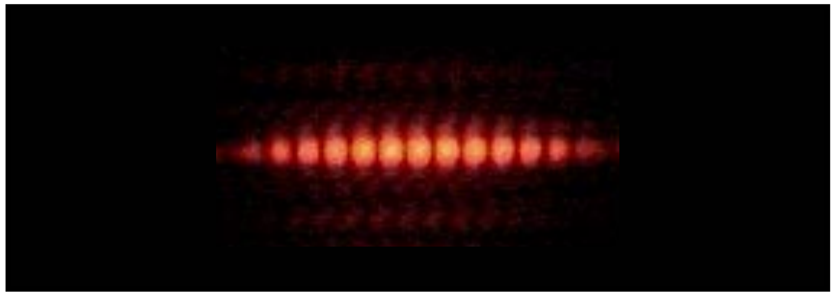
The Young Two-slit experiment

With classical light:

T. Young



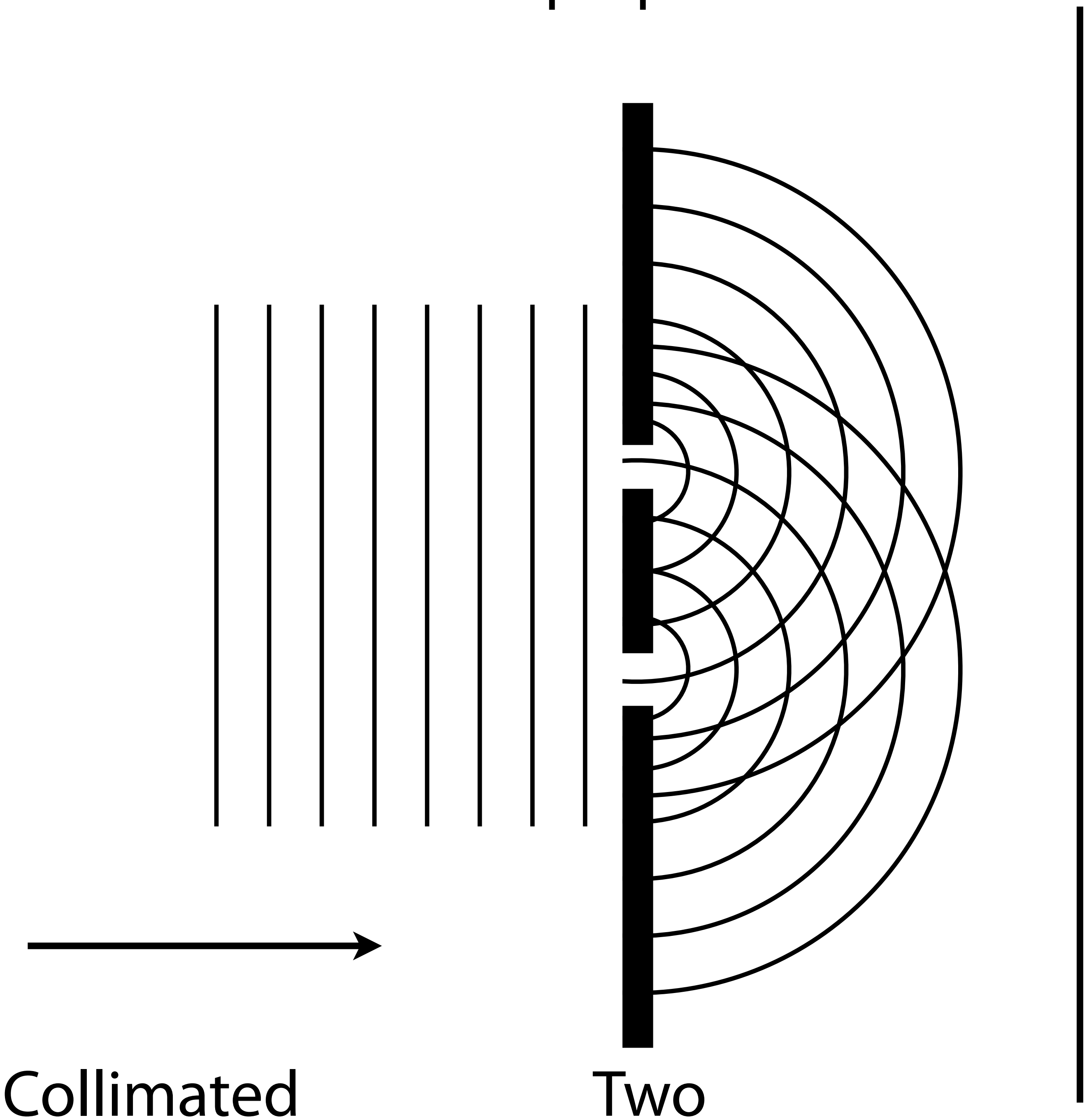
What we observe on the screen



The Young Two-slit experiment

With single photons?

T. Young



What do we observe?

The Young Two-slit experiment

with single photons.

T. Young

This is a video of a two-slit experiment with single photons.

The Young Two-slit experiment

with single photons.

T. Young

This is a video of a two-slit experiment with single photons.

Universiteit Leiden

0,025 msec

Universiteit Leiden

0,025 msec

The Young Two-slit experiment

with single photons.

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The experiment satisfies the probability rule: **single photon probability** proportional to classical light **intensity**.

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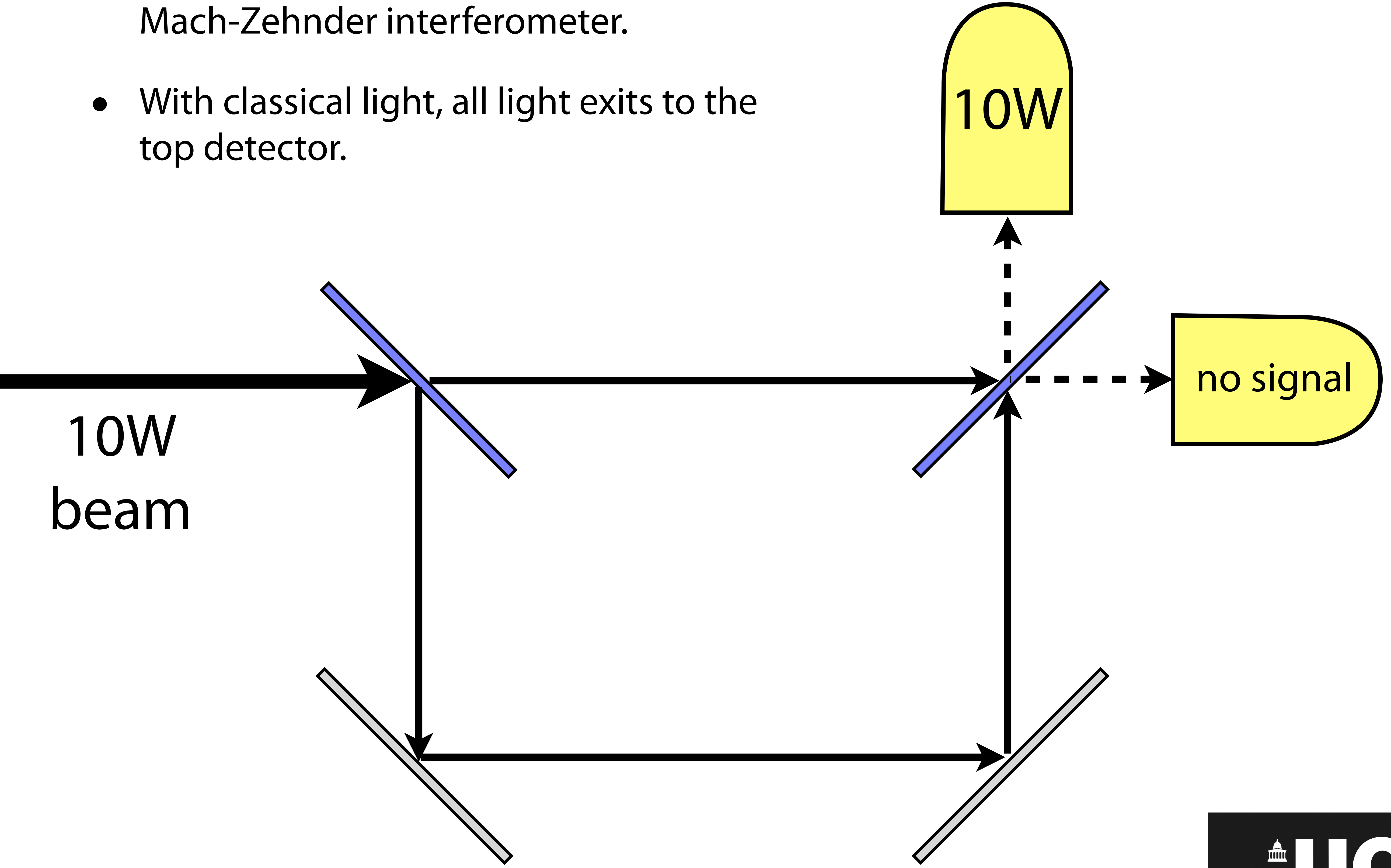
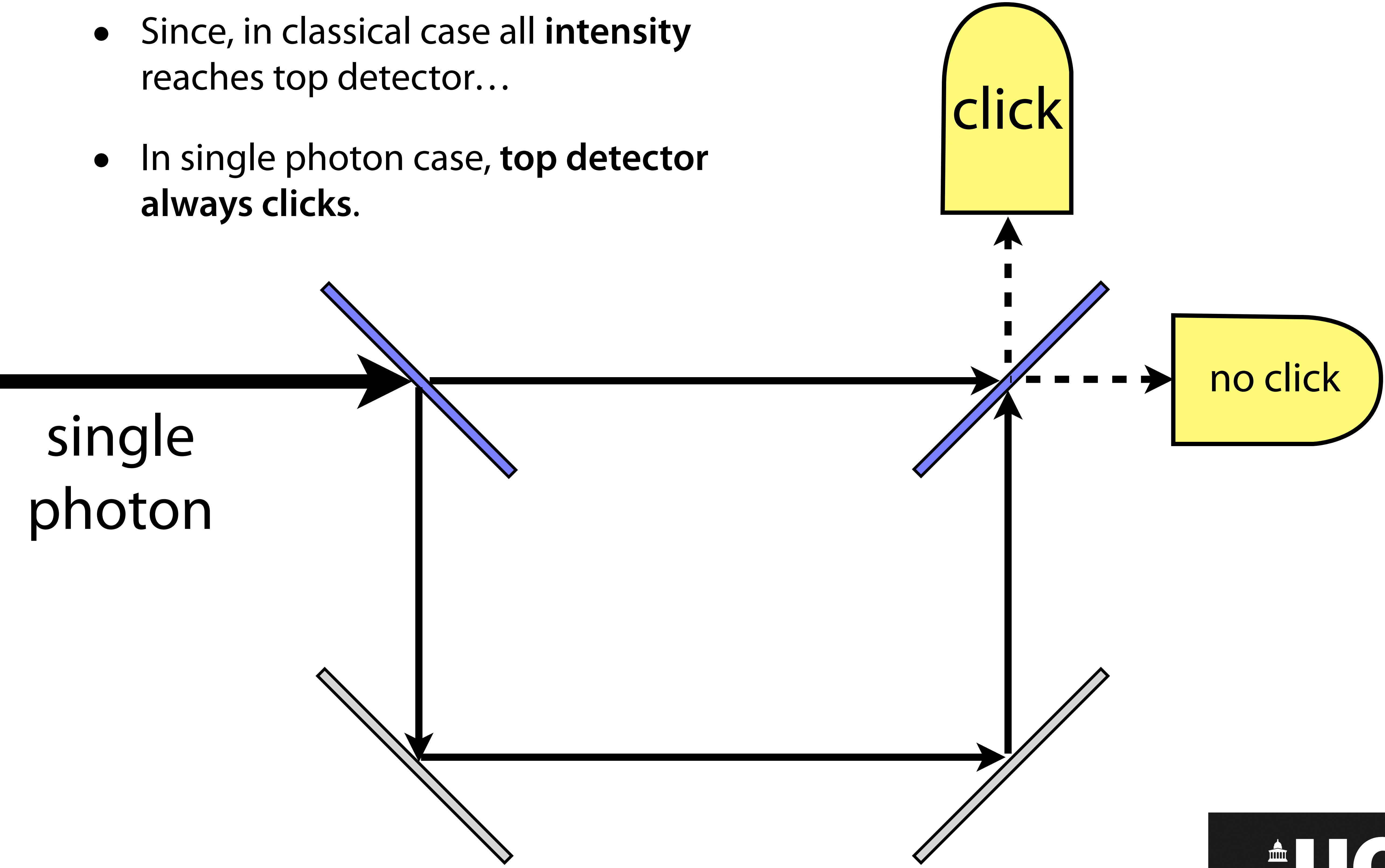
Mach-Zehnder interferometer

- Now let's consider single photons in the Mach-Zehnder interferometer.
- With classical light, all light exits to the top detector.



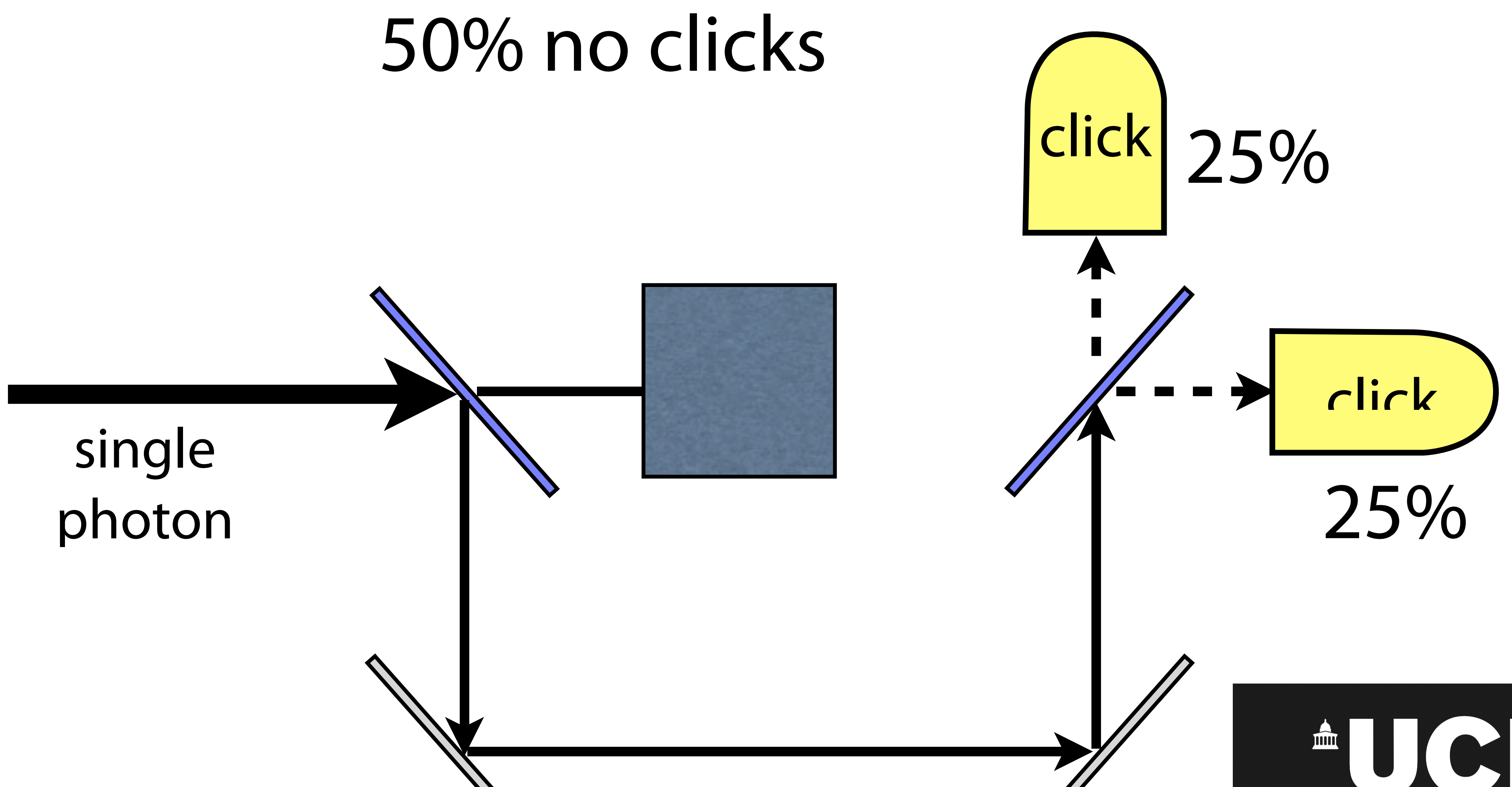
Mach-Zehnder interferometer

- We apply the probability rule:
- Since, in classical case all **intensity** reaches top detector…
- In single photon case, **top detector always clicks**.



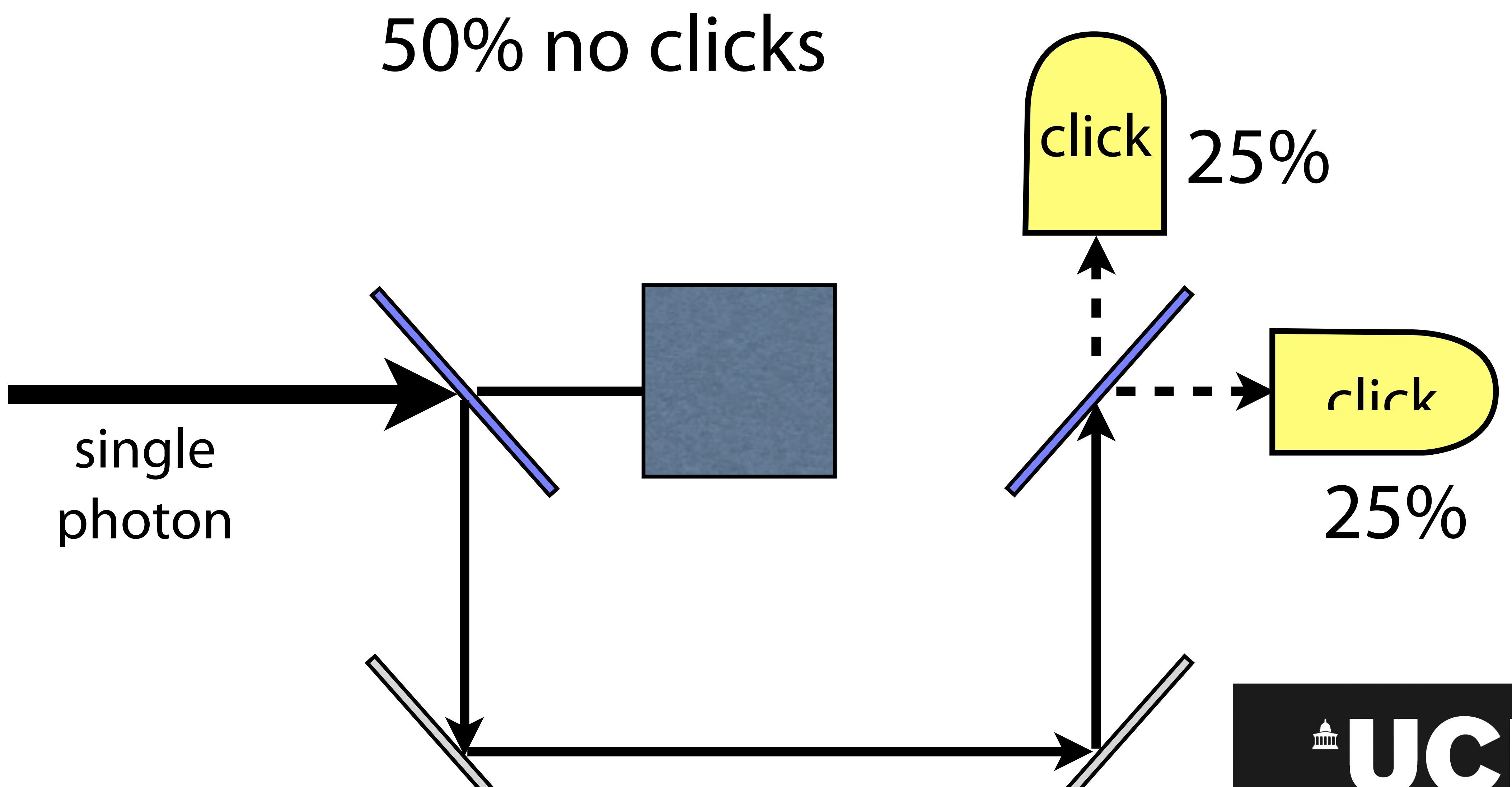
Wave-particle duality of the photon

- What happens when we block one of the paths?
  - The **probabilities** match the intensities of the classical light.
  - **50% chance** - photon is absorbed by the barrier - **no click** at either detector.
  - **25% equal chance** - **either** one of the **two detectors**.



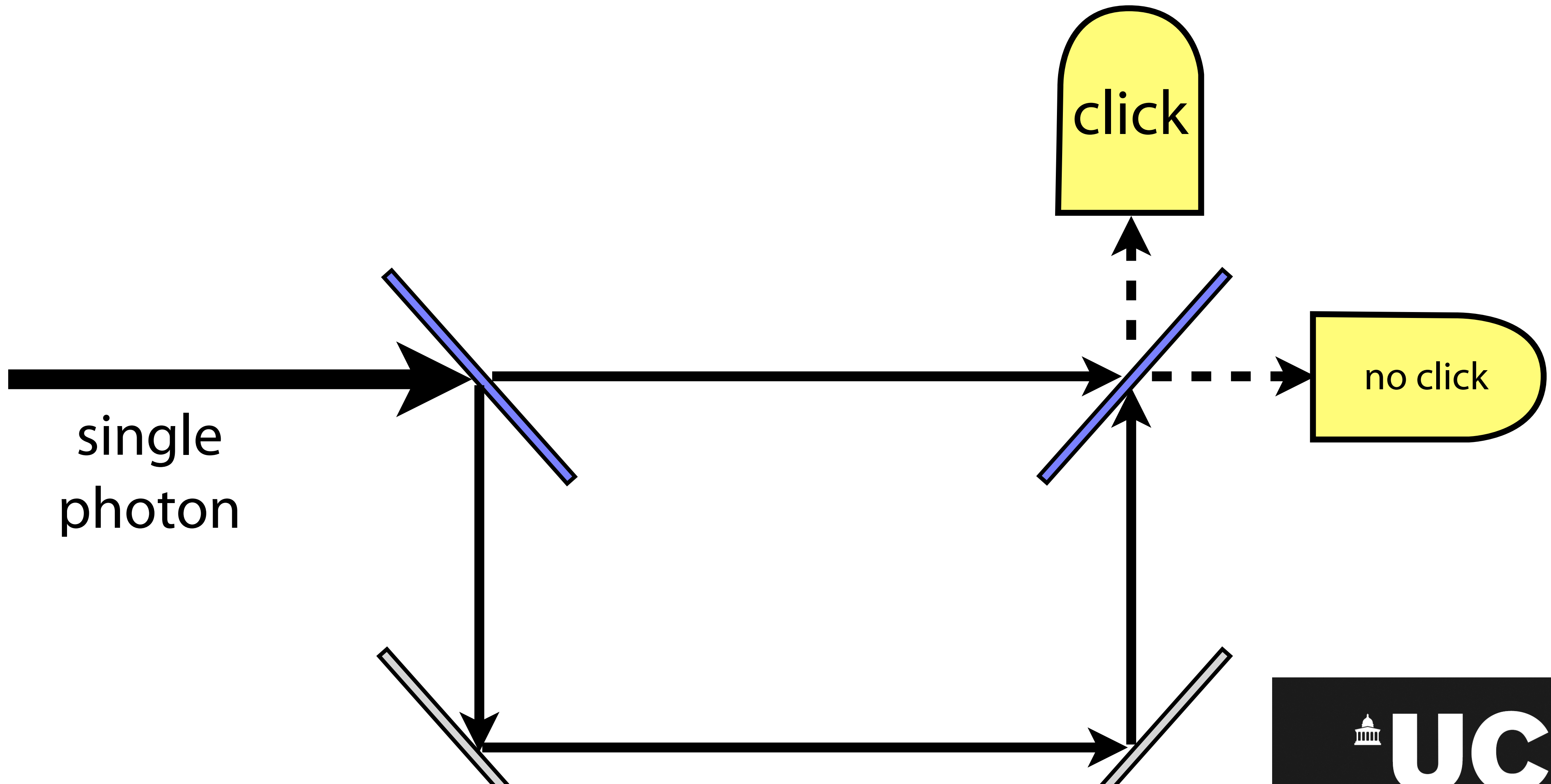
Wave-particle duality of the photon

- If no path is blocked - the photon can **never** reach detector 2.
- But if either path is blocked - the photon **can** reach detector 2.
    - So - the photon must "know" about both paths.



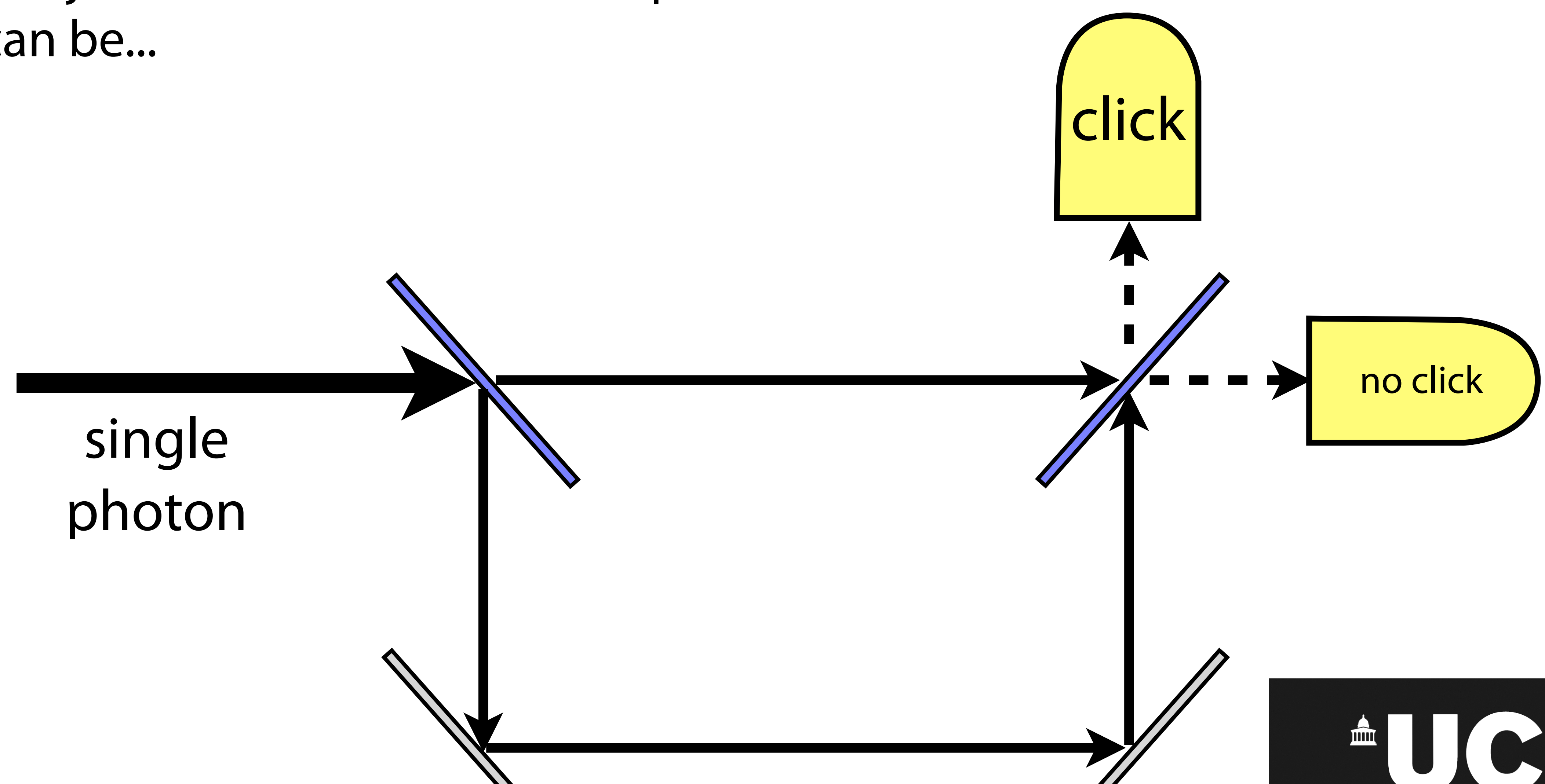
Wave-particle duality of the photon

- This cannot be explained in classical physics. The photon behaves both like a wave - and a particle.
- When **travelling**, a photon behaves like a wave (e.g. taking both arms in the interferometer).
- When **detected,** a photon behaves like a particle - it can only **click** in **one detector** (following our probability rule)**.**



Measurement in quantum physics

- This illustrates a crucial non-classical aspect of quantum mechanics
  - **Measurement** has a direct effect on the **measured system**.
  - When **not observed**, the photon behaves like a **wave**.
  - When **measured**, the photon behaves like a **particle**!
- This is a hint of just how counterintuitive quantum mechanics can be...



Summary of Part 1

- We saw that the **wave** model was the correct classical model of light, as **only** this model can explain **interference** experiments.

- We saw evidence, (Black-body radiation, Photo-electric effect) that light is **absorbed** and emitted as **packets** of **energy**.

- Planck's energy of a **photon**: $\mathbf{E = hf}$

- We saw that **single photon behaviour** can be **observed**. Photons are detected as **"clicks"** in a **photon detector**.

- **Classical** - **Quantum** correspondence in **interferometers**:

  - **probability** of **photon** reaching a detector is **proportional** to **intensity** in classical experiment.

- We saw that the behaviour of **single photons** in a **Mach-Zehnder** interferometer **cannot** be explained by **wave-like** or **particle-like** behaviour alone.