Part 1: Waves as Particles - The Photon

Aims of Part 1

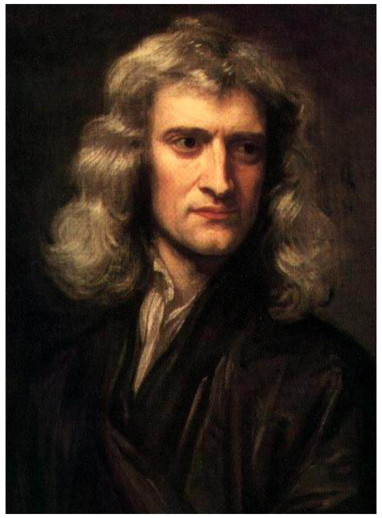
- To take a brief historical tour of the competing wave and particle pictures of light.
- Consider evidence from interference experiments that light is a wave.
- Consider evidence that indicate that light is not a wave.
- To introduce the photon,
  - and by studying interference experiments learn that 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?

Light: A wave or a particle?

Ole Rømer

Christiaan Huygens



Isaac Newton

- 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

Images from Wikipedia

Aside: Where are the women?

University of Copenhagen, admitted its first female undergraduate in 1877

University of Leiden, admitted its first female undergraduate in 1873 (for two weeks) and then 1878

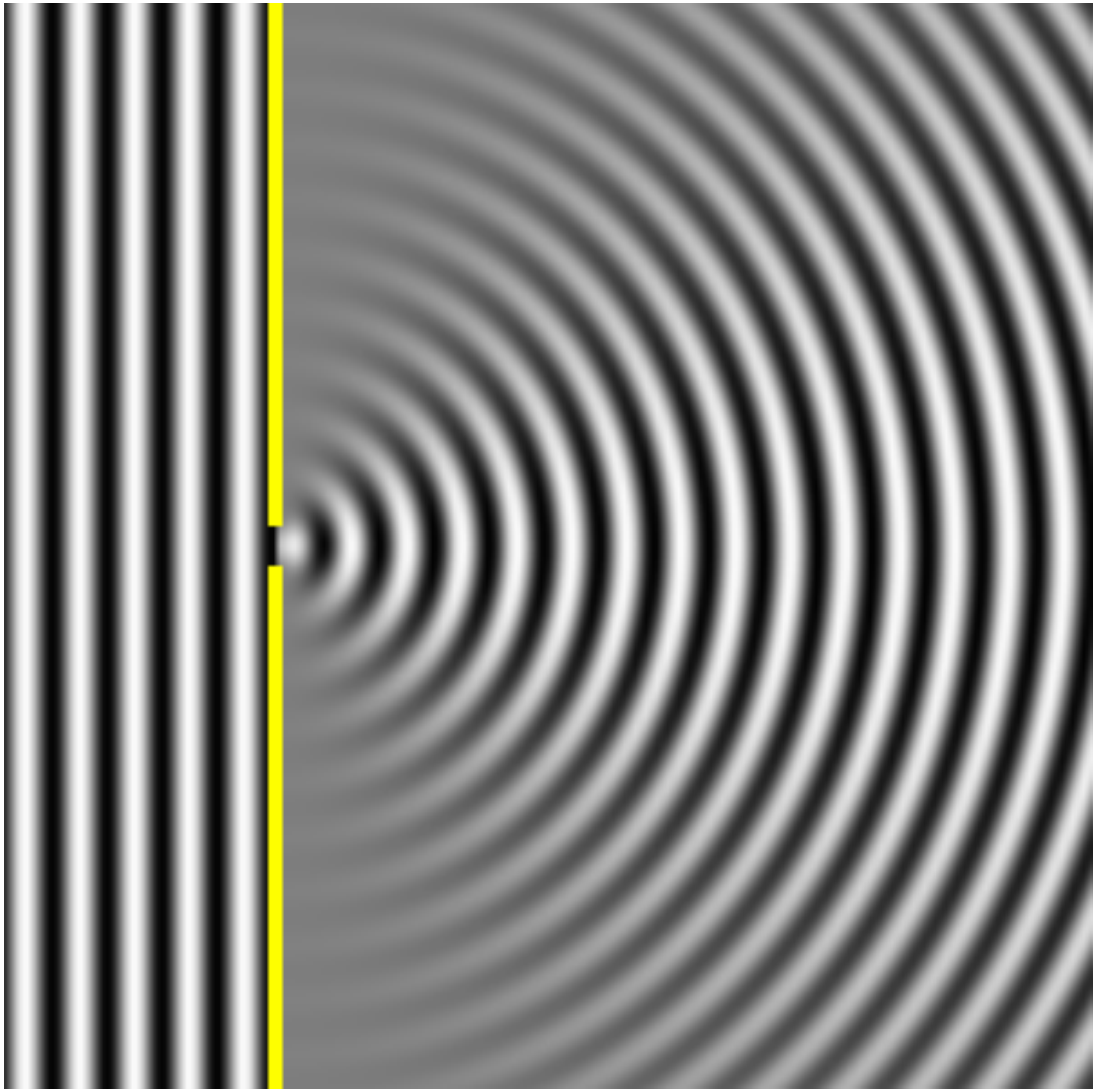
First female colleges 1869, first examined 1882, first female full members 1948

Claims to be first university in England to admit women on equal terms in 1878

Difference between particles and waves?

Interference!

Aside: Diffraction



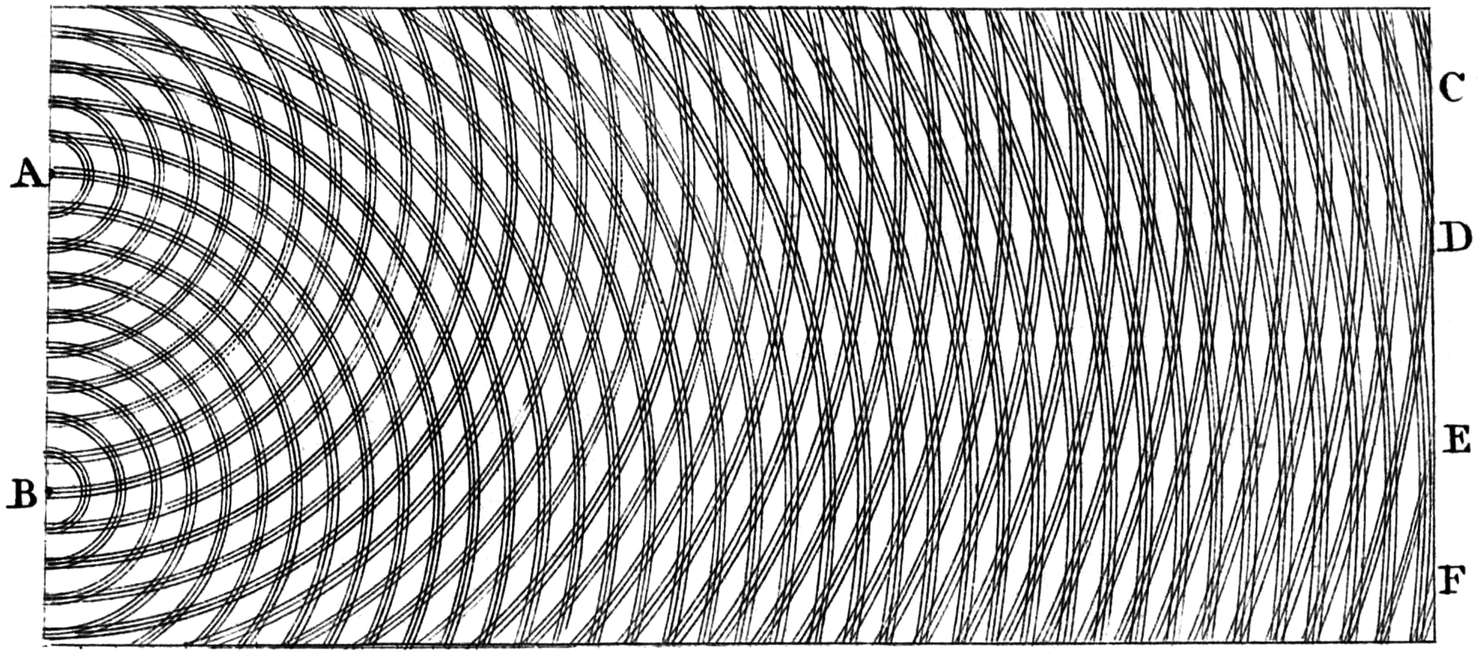
gif from Wikipedia / Wikimedia Commons

- When a plane wave encounters a slit, you get diffraction
  - First described by Francesco Grimaldi in 1660
  - Aside within aside:
    - Reflection was first described by Euclid in 300 BC
    - Refraction first accurately described by Ibn Sahl in 984

Young's Double-slit experiment

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

Thomas Young



Thomas Young's sketch of two-slit diffraction

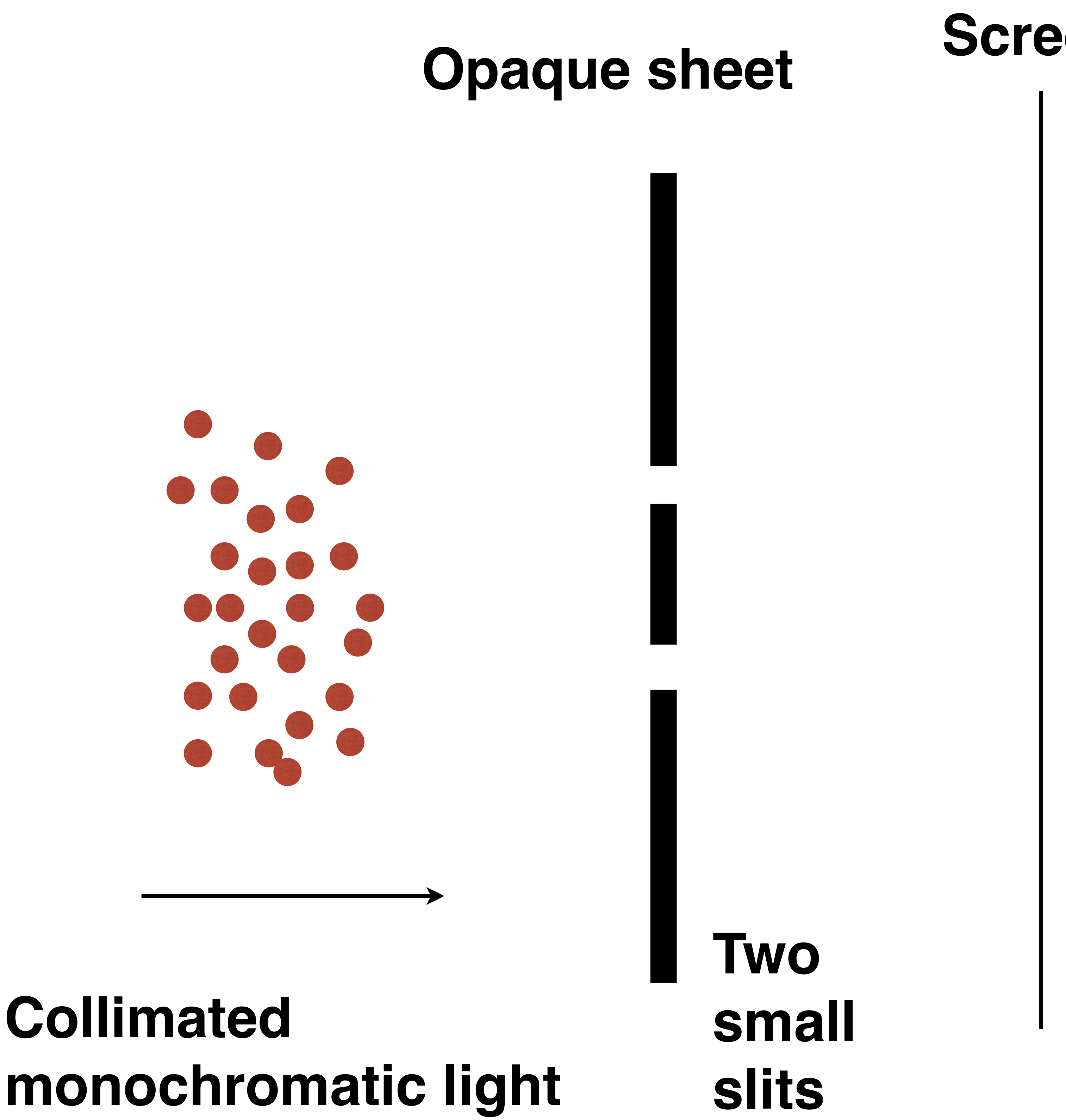
Poll

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

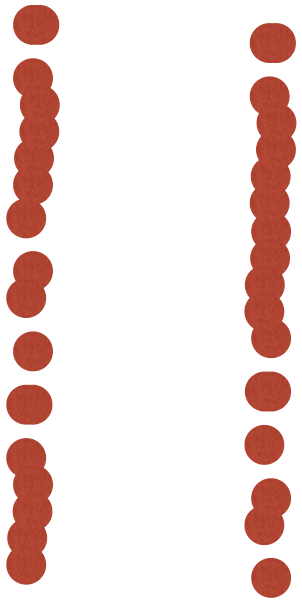
Young's Double-slit experiment

If light were made of particles

T. Young



What would we observe on the screen?

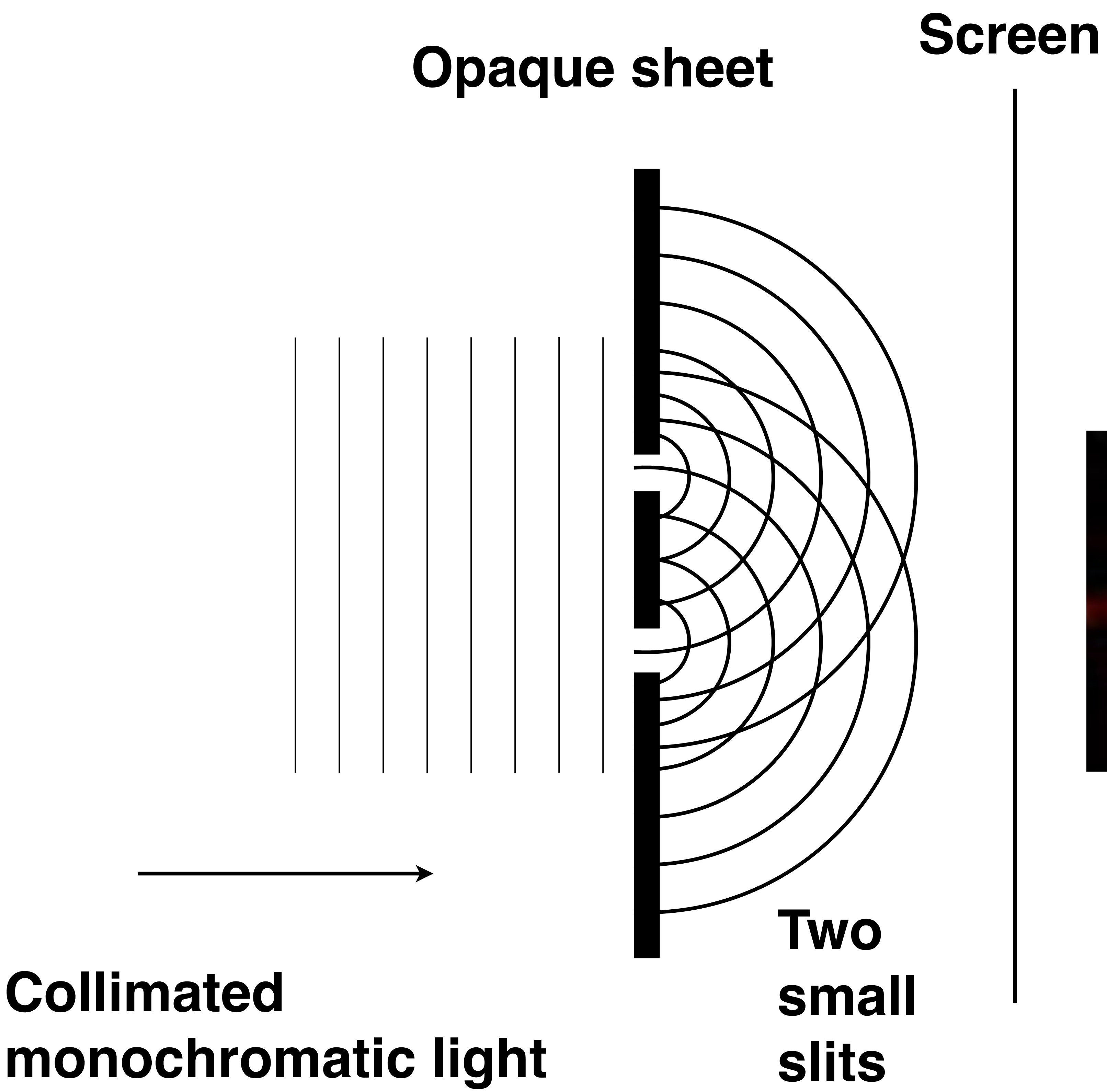


Front view

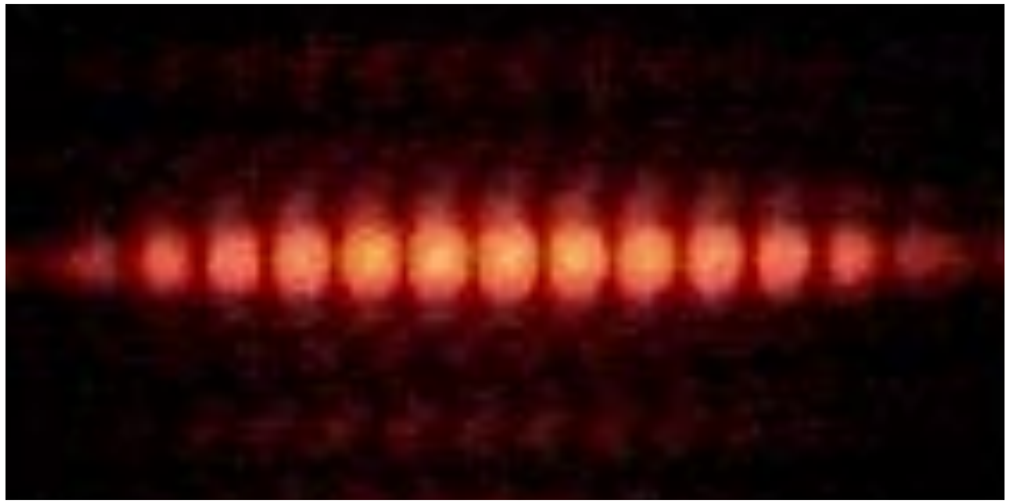
Young's Double-slit experiment

Details: Jewett and Serway, Chapter 37

T. Young



What we observe on the screen

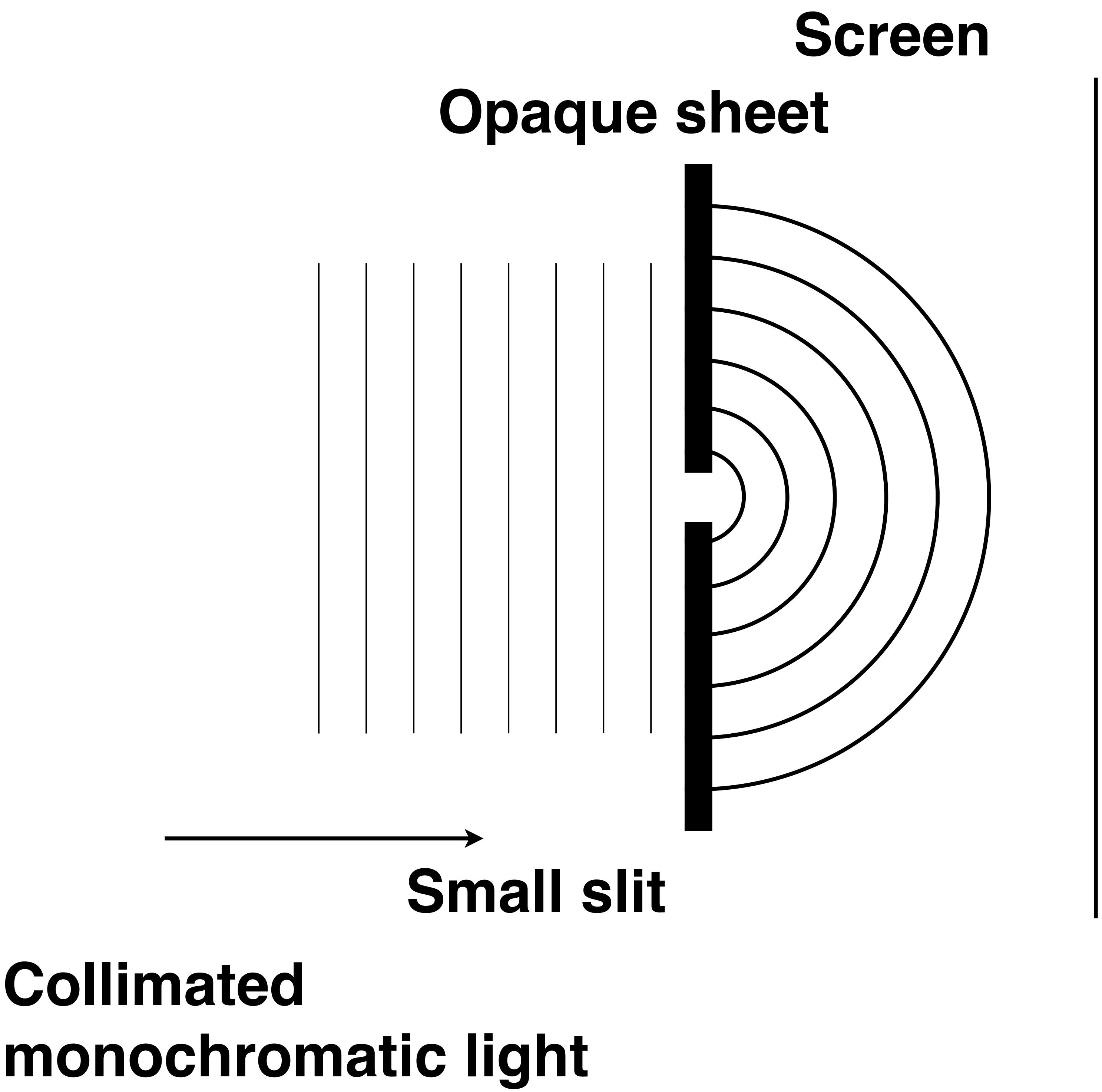


Front view

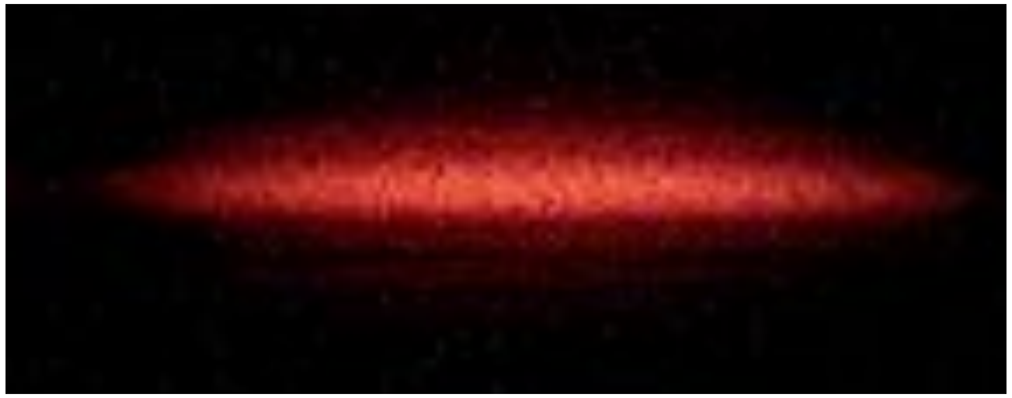
Young's Double-slit experiment

–If we **block one slit**:

T. Young



What we observe on the screen

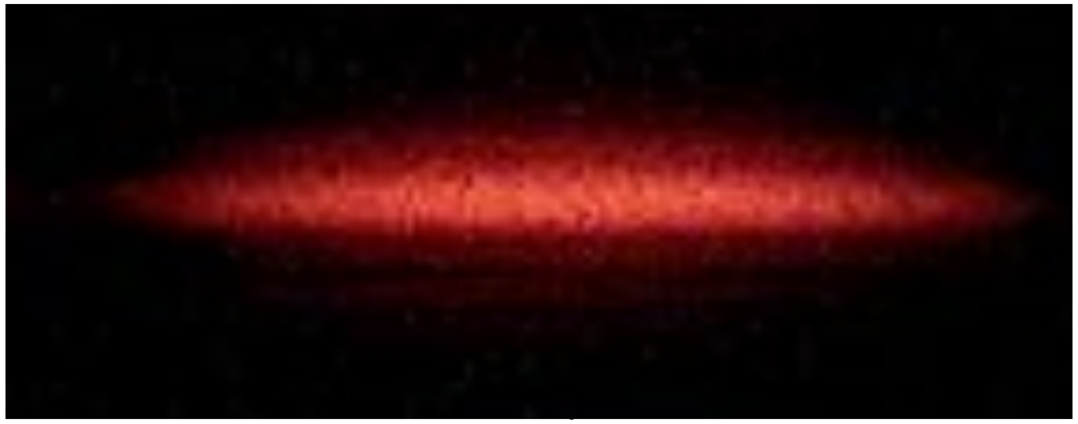


Young's Double-slit experiment

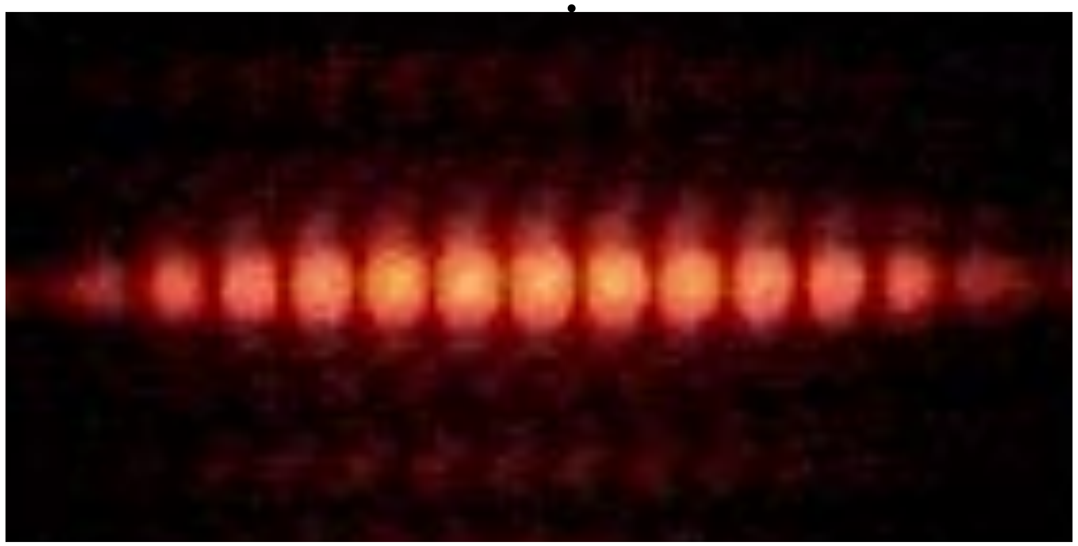
–Consider a spot which is **dark** in the two slit pattern.

T. Young

One slit



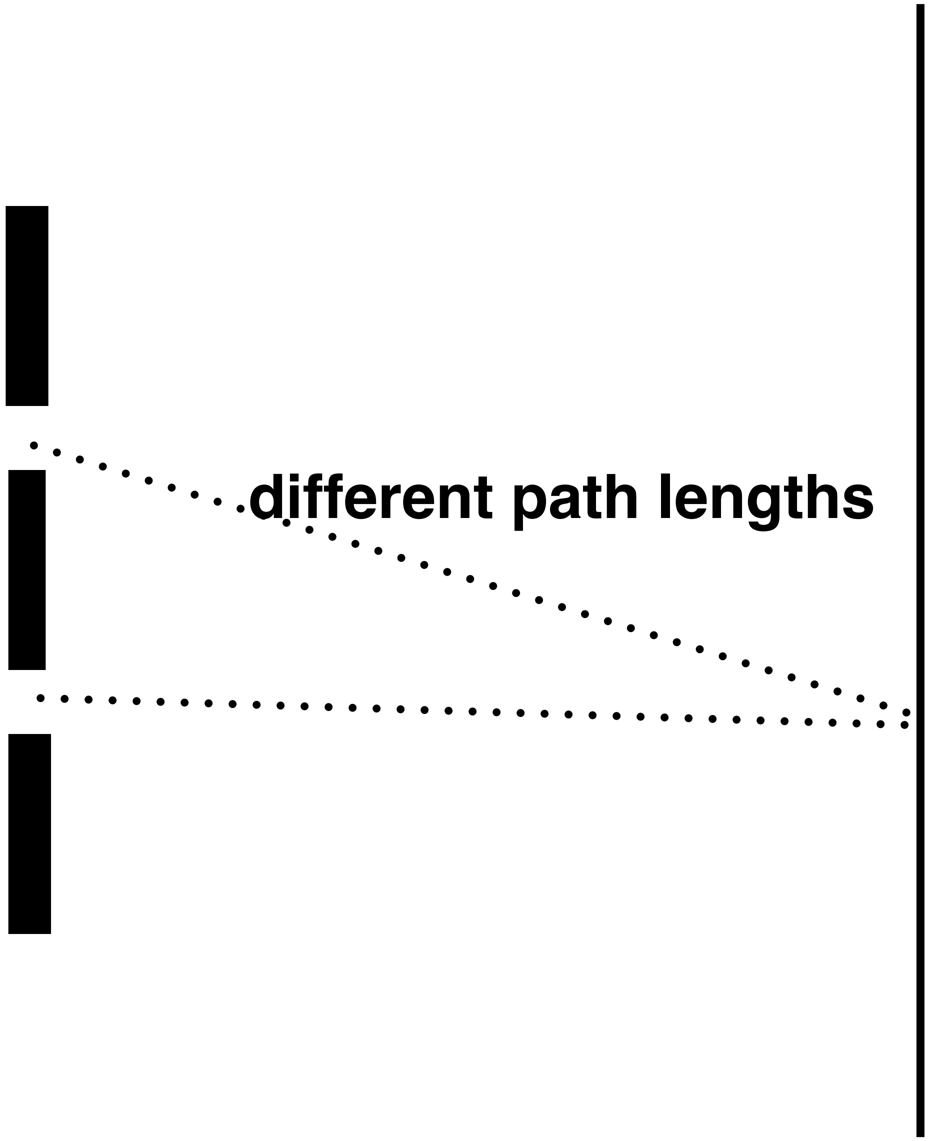
Two slits



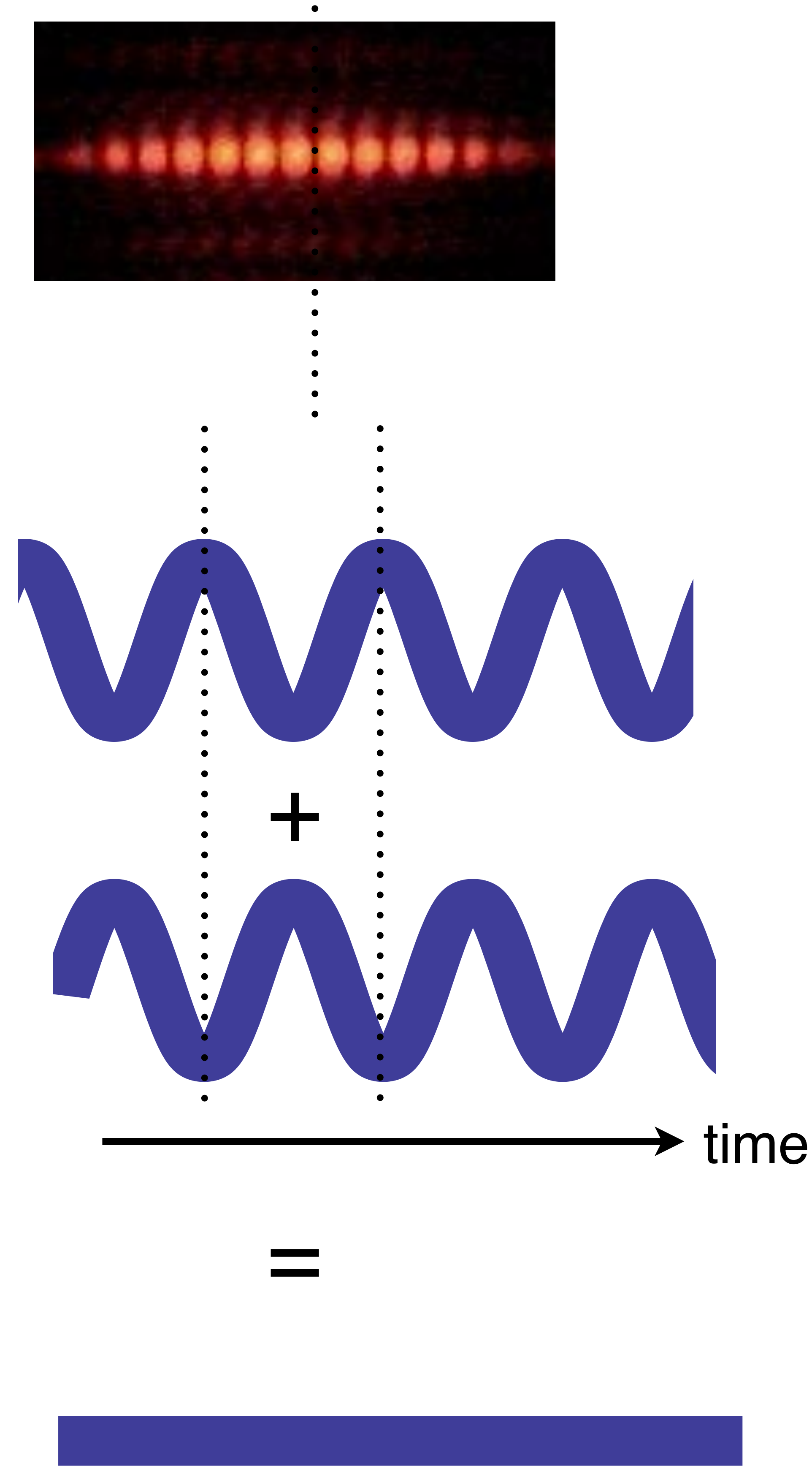
–Note that opening the 2nd slit (providing extra light) has made this point **darker**!

Young's Double-slit experiment

At the dark spots.



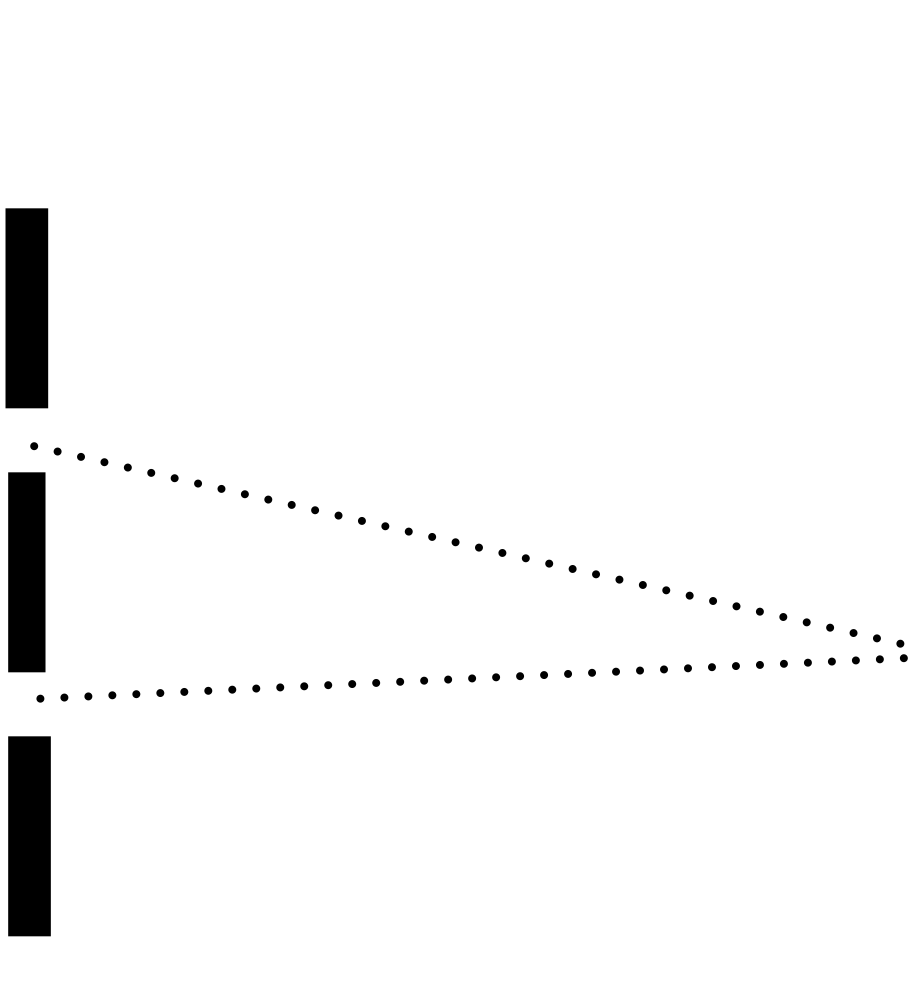
"in-antiphase"

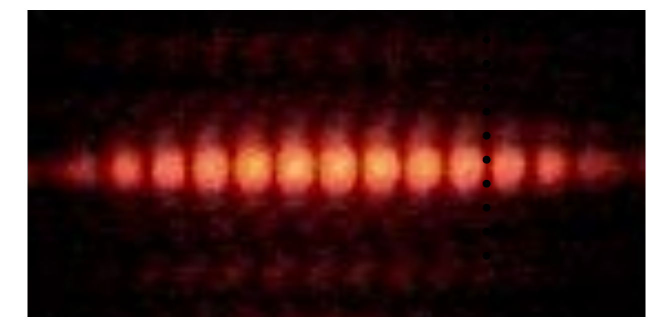


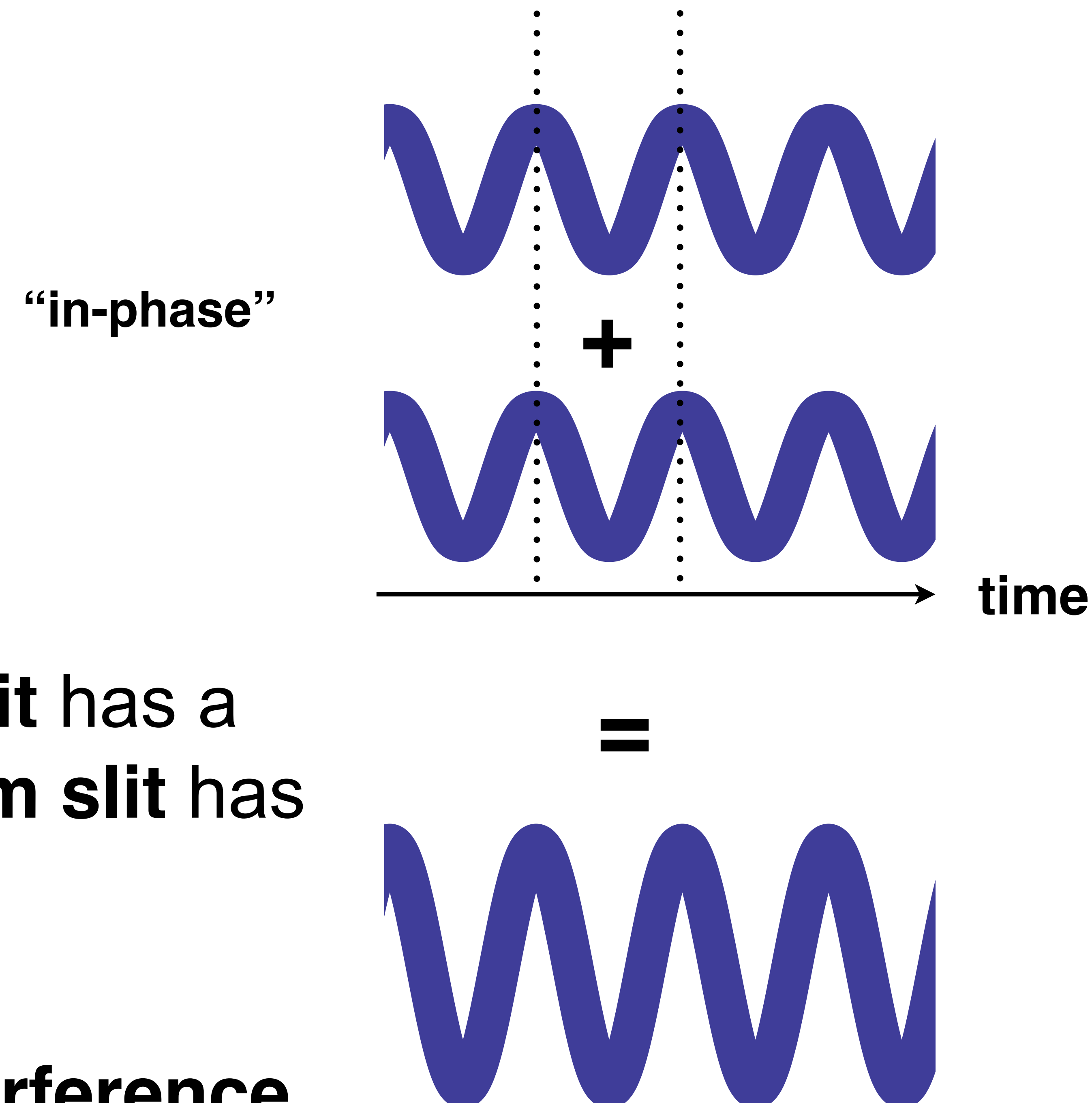
- –When the light from the **top slit** has a **peak**, the light from the **bottom slit** has a **trough**.
- –The waves **cancel out**.
- –We call this **destructive interference**.

Young’s Double-slit experiment

At the bright spots.





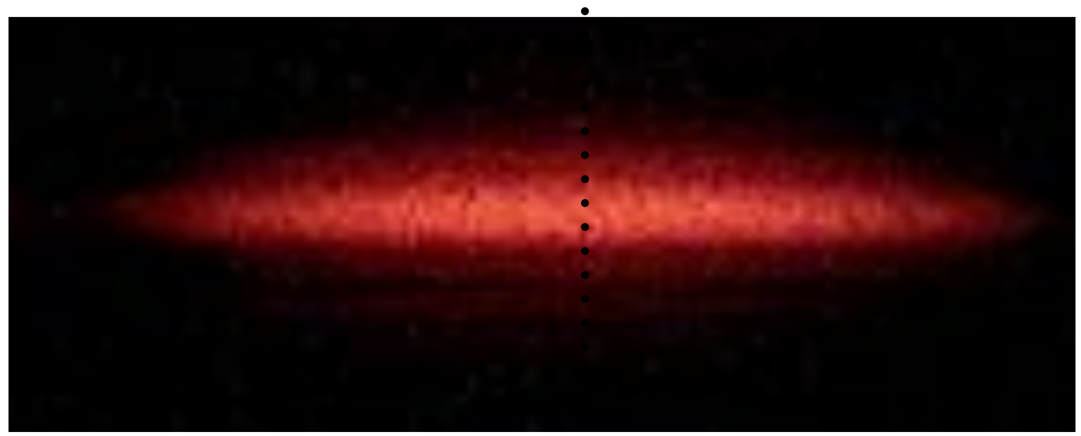


- When the light from the **top slit** has a **peak**, the light from the **bottom slit** has a **peak**.
- The waves **add up**.
- We call this **constructive interference**.

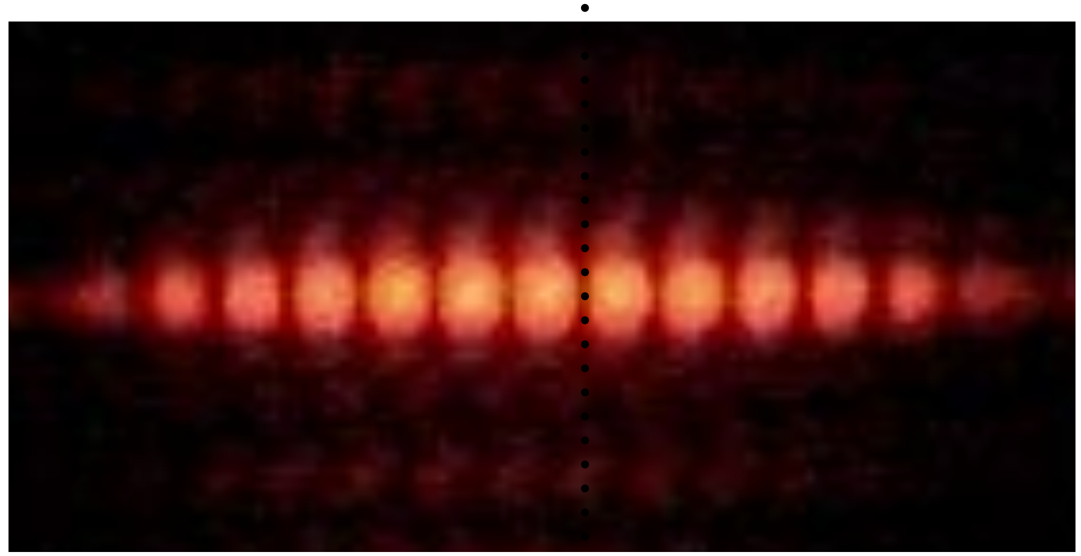
Young's Double-slit experiment

–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***...)

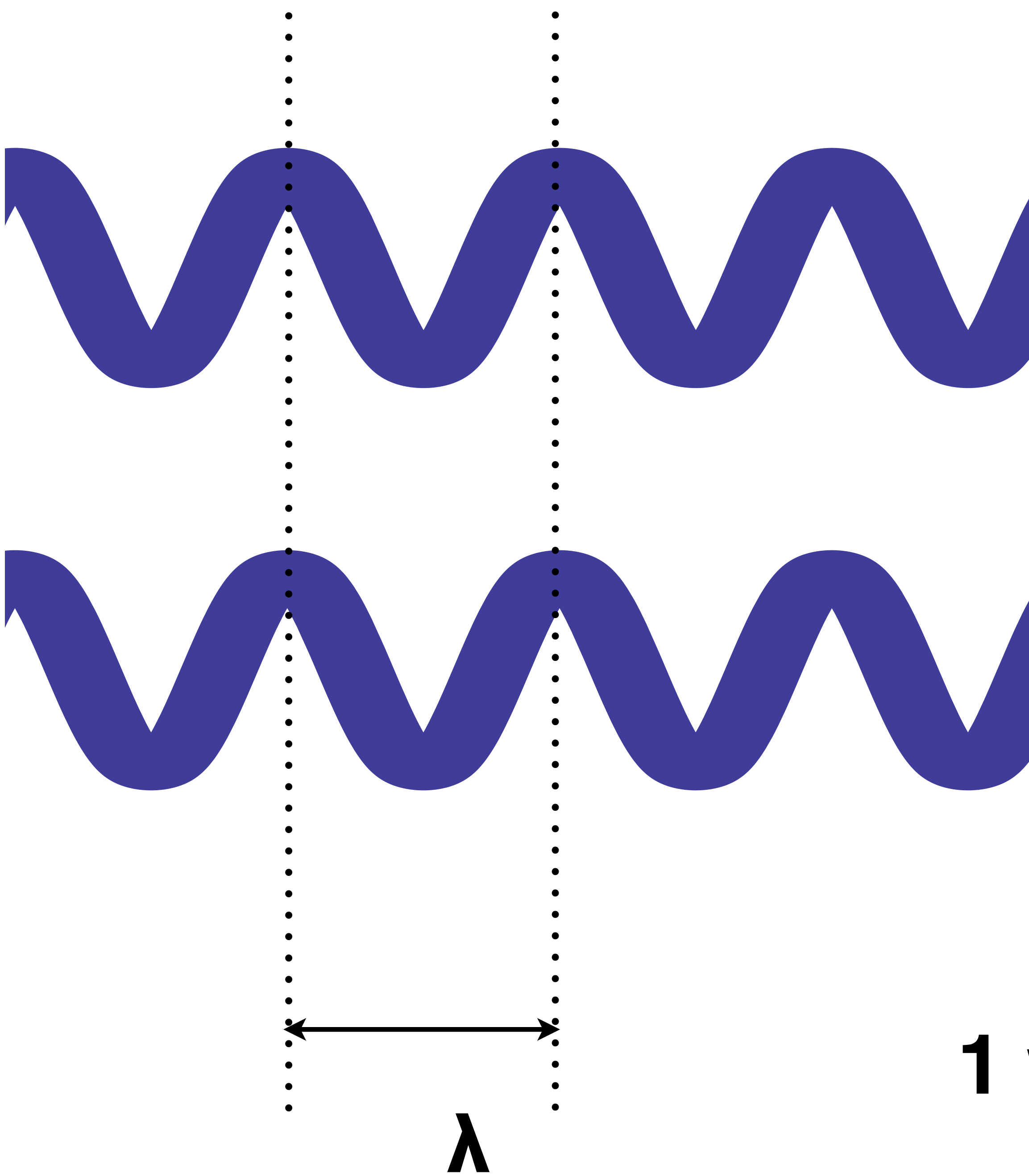
Phase shift

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

Phase shift

- Examples

1/2 wavelength phase shift

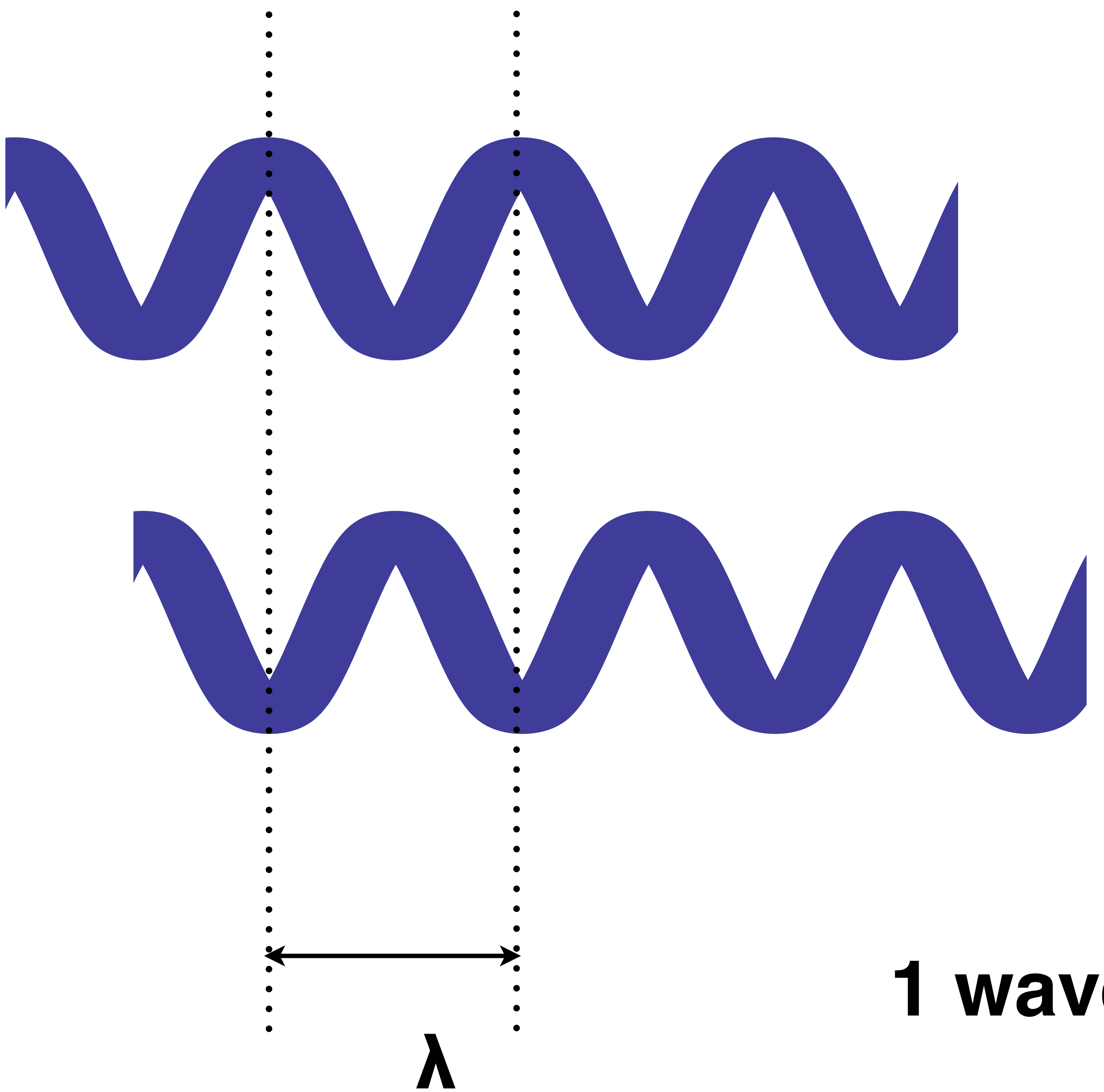


1 wavelength

Phase shift

- Examples

1/2 wavelength phase shift



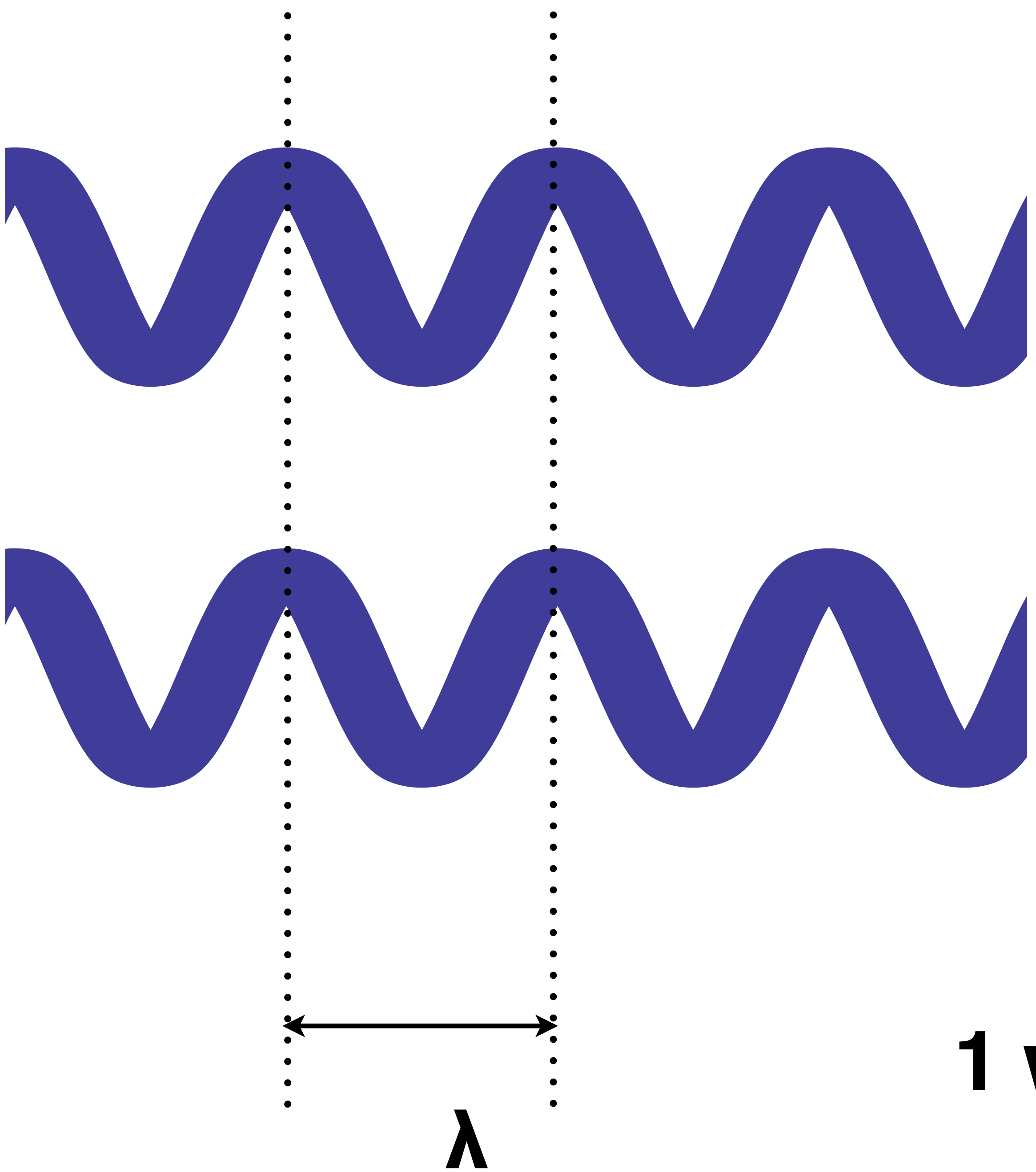
The waves are now in anti-phase and will destructively interfere.

1 wavelength

Phase shift

- Examples

Whole wavelength phase shift

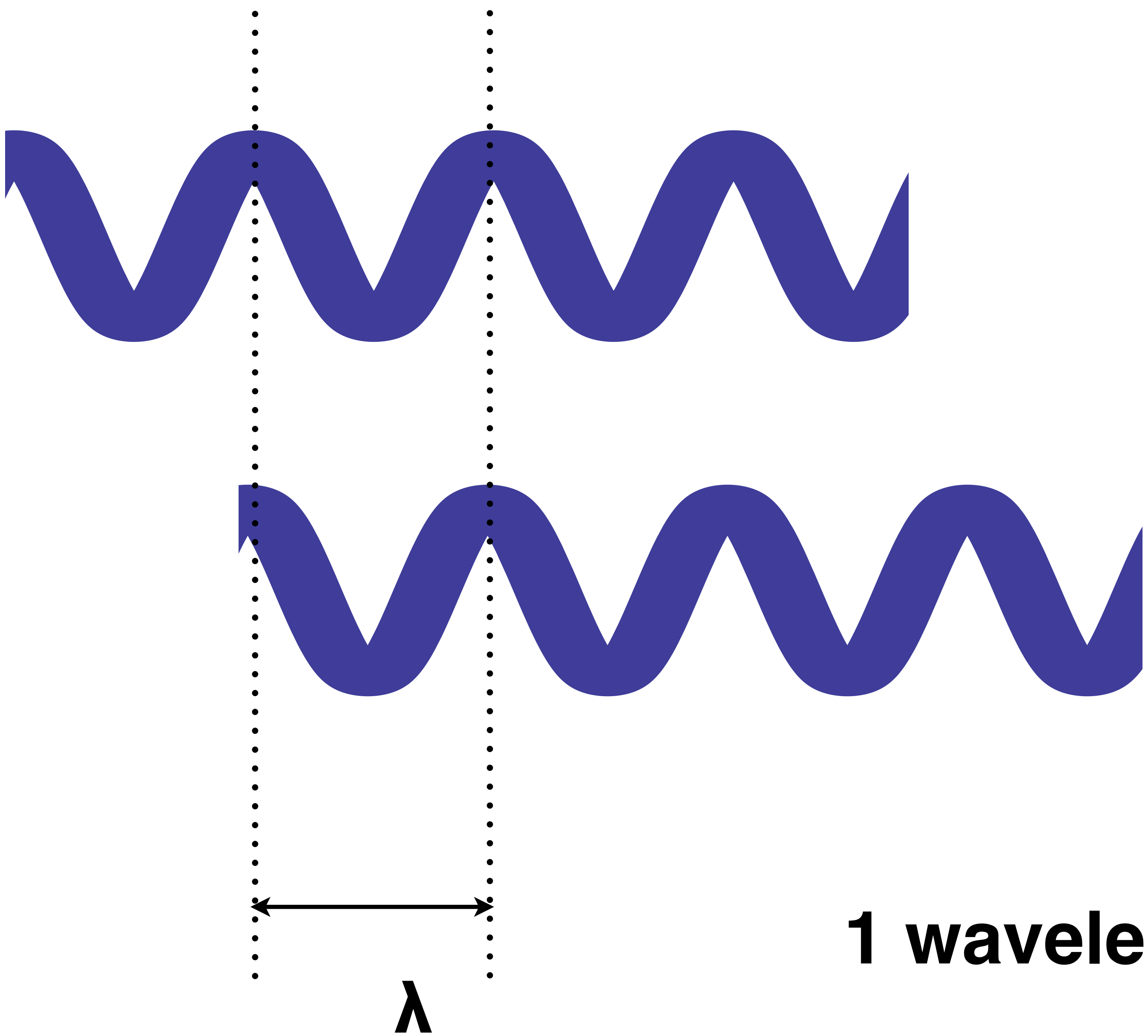


1 wavelength

Phase shift

- Examples

Whole wavelength phase shift



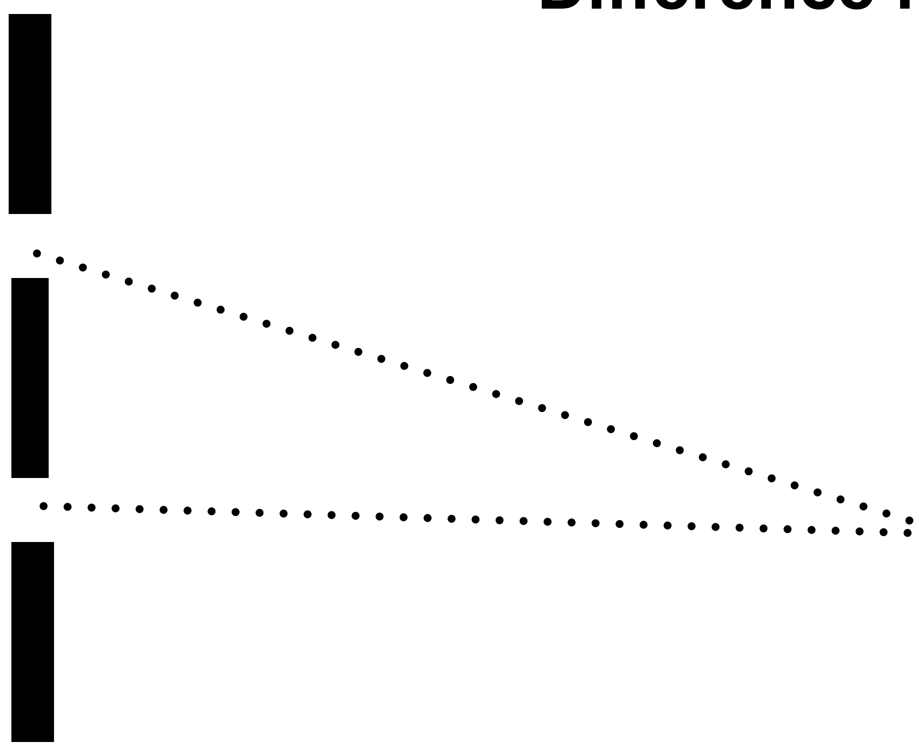
The waves are now in phase and will constructively interfere.

1 wavelength

Phase shift

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

Difference in path length

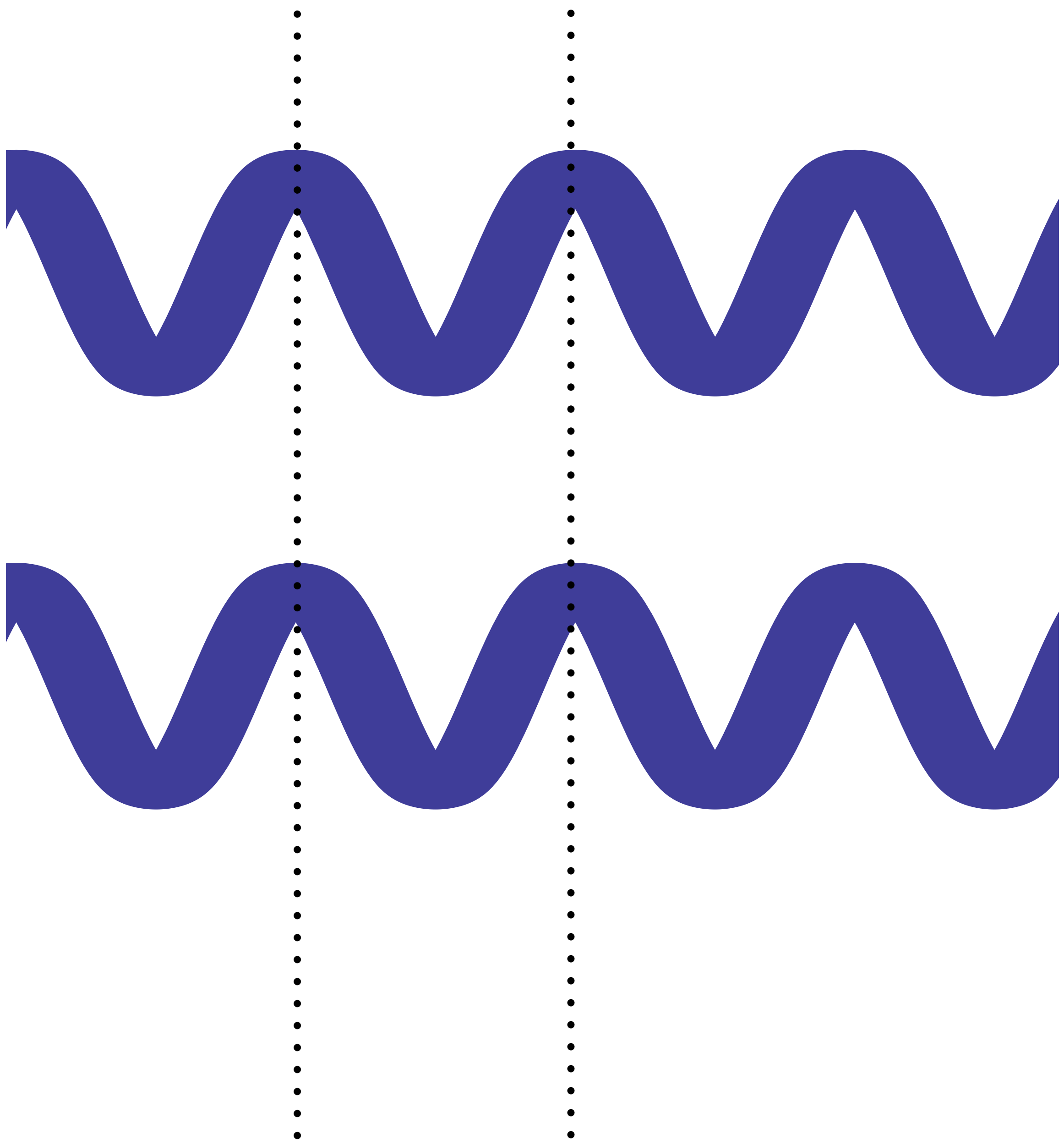


Passing through a crystal

- **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:



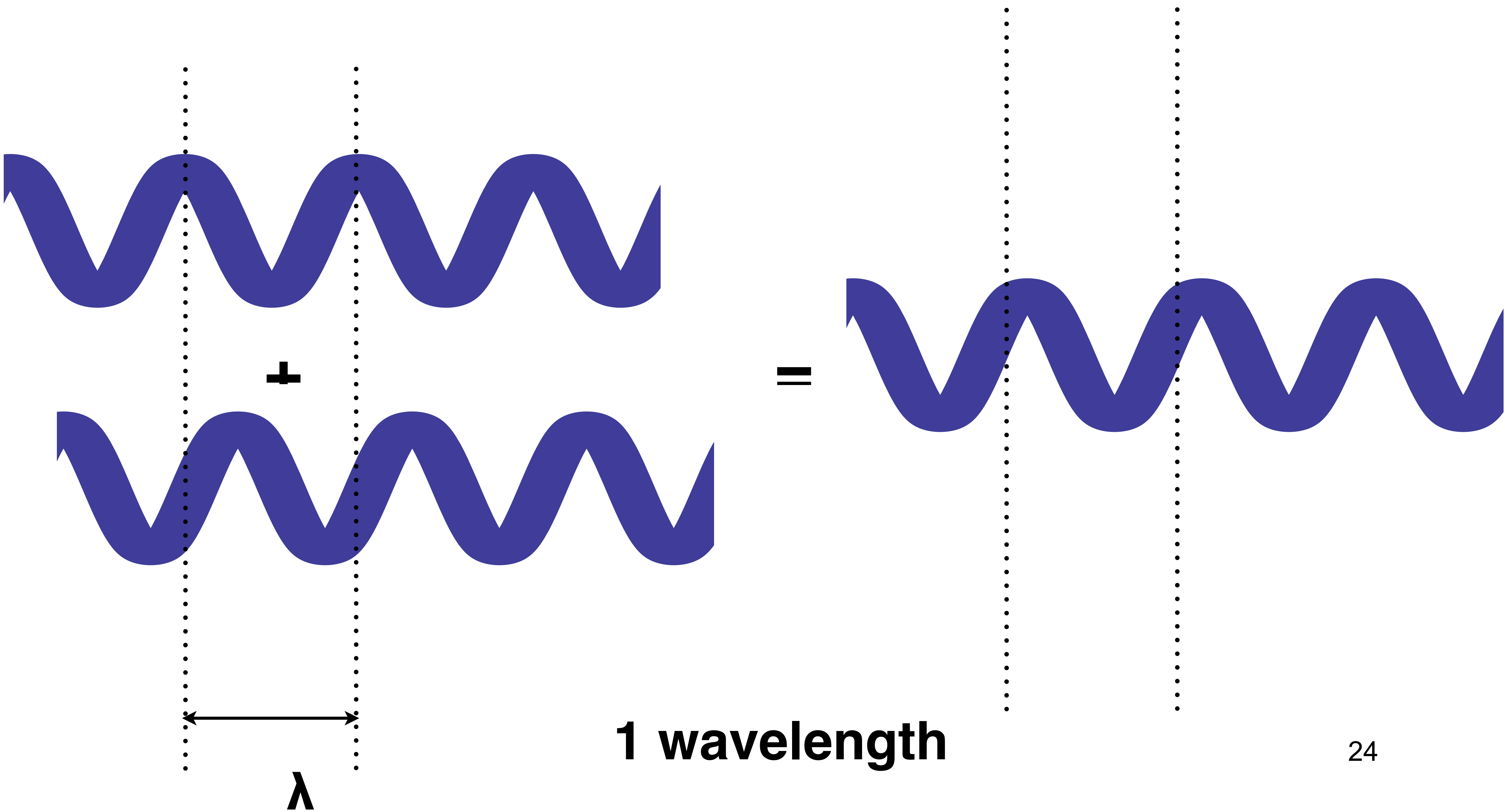
- 1. In phase
- 2. In anti-phase
- 3. Neither in phase or anti-phase.

Phase shift

- Examples

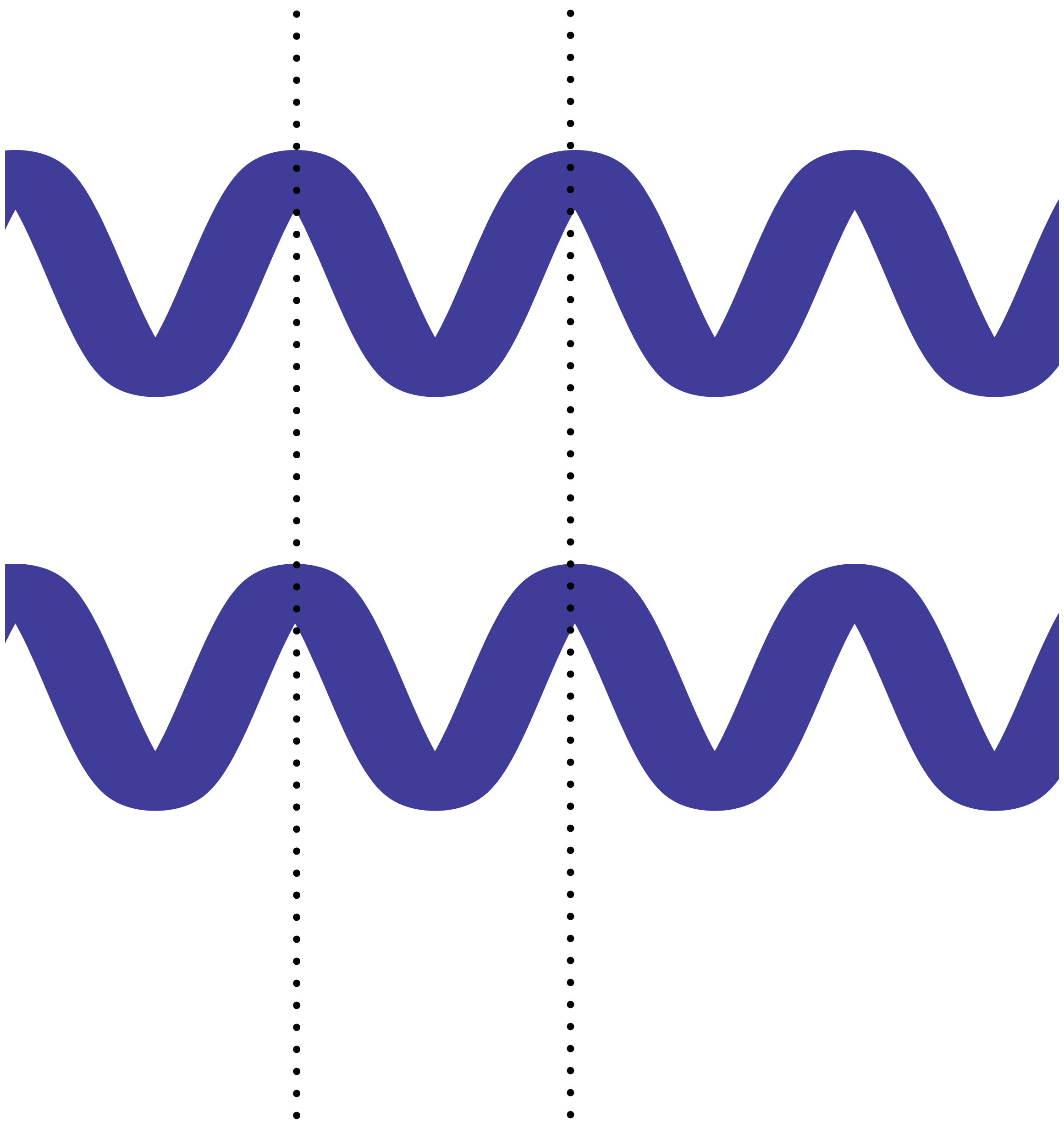
The waves are neither in phase or in antiphase but half-way in between

1/4 wavelength phase shift



Quiz

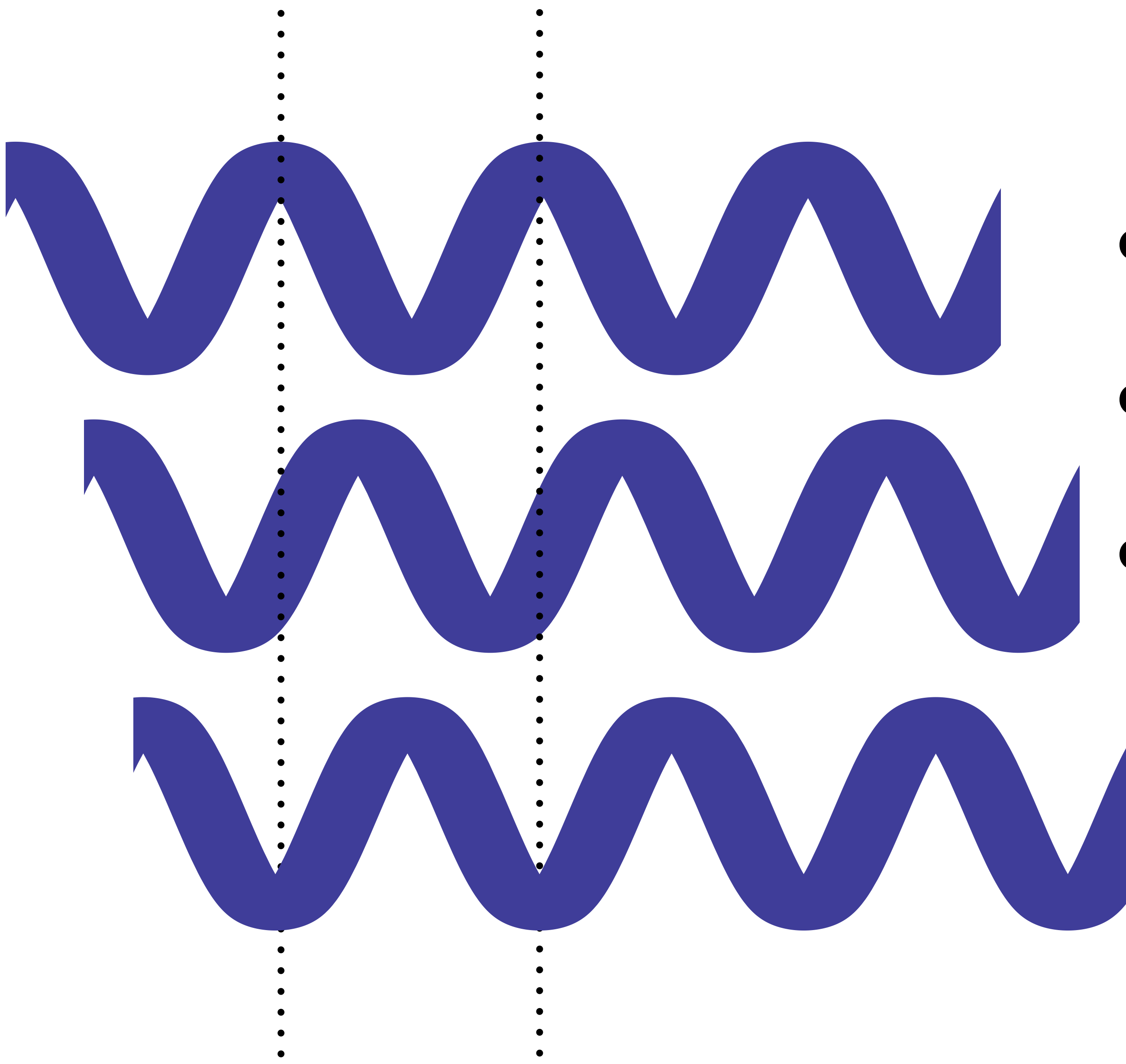
- If I have two beams of light which are initially in phase and I then give the second beam a 1/4 wavelength phase and then give it another 1/4 wavelength phase-shift, will the beams be:



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

Quiz

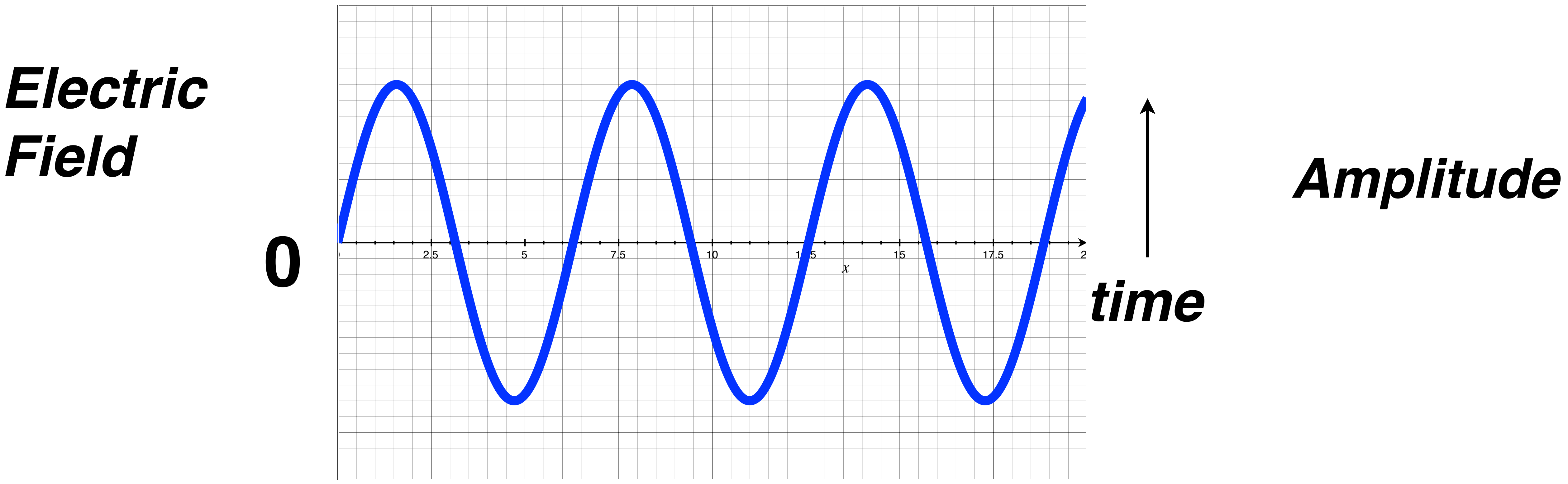
- If I have two beams of light which are initially in phase and I then give the second beam a 1/4 wavelength phase and then give it another 1/4 wavelength phase-shift, will the beams be:



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

Aside: Intensity vs Amplitude

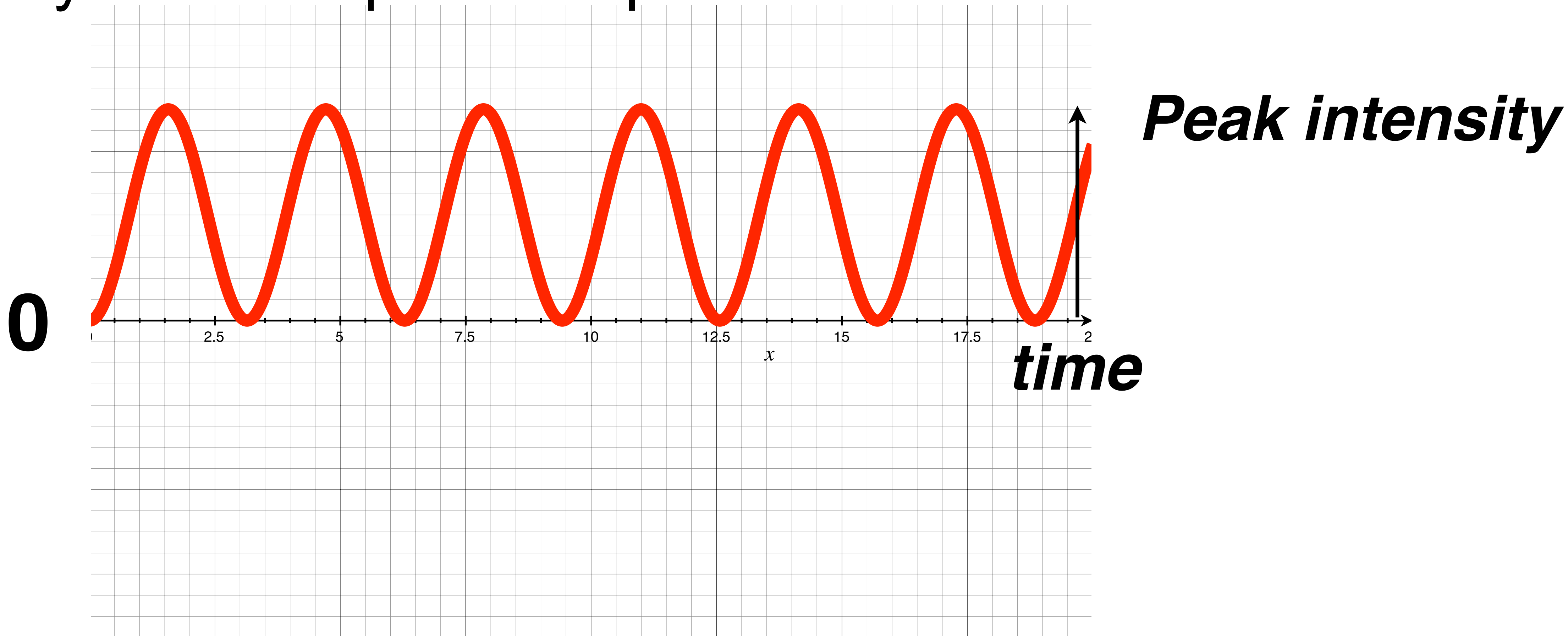
- (Classical theory of) light
  - –A wave in electric and magnetic fields.



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

Aside: Intensity vs Amplitude

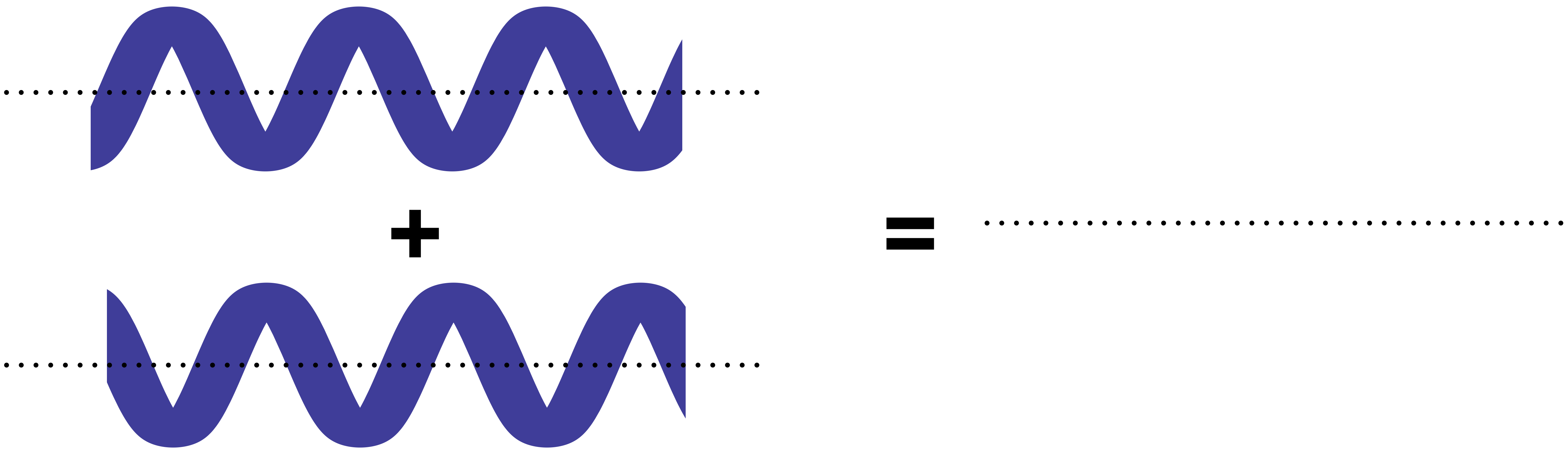
- (Classical theory of) light
  - –Intensity is the amplitude squared.



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

Aside: Intensity vs Amplitude

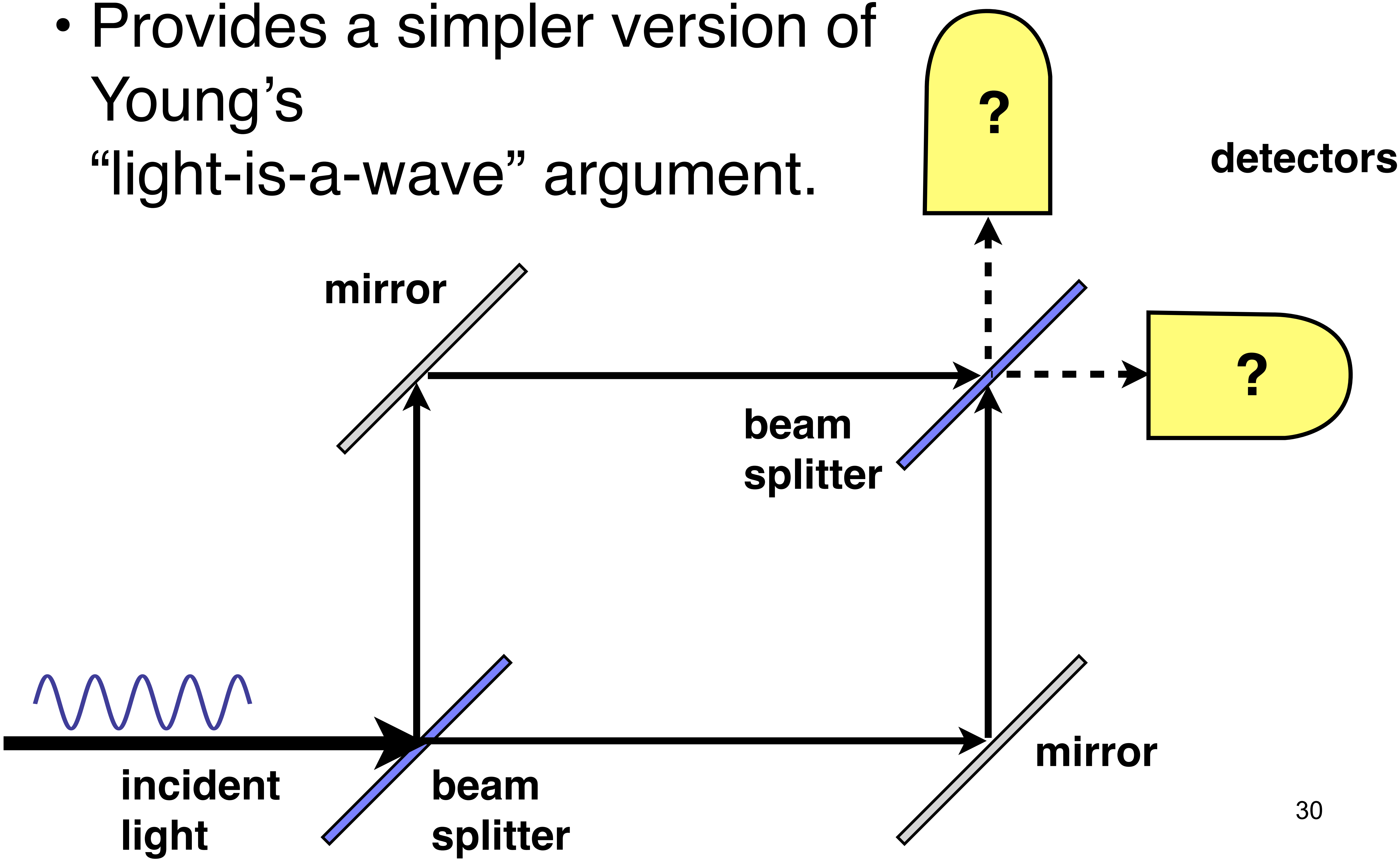
- (Classical theory of) light
  - –Interference happens on the level of **amplitudes**.



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

The Mach-Zehnder interferometer

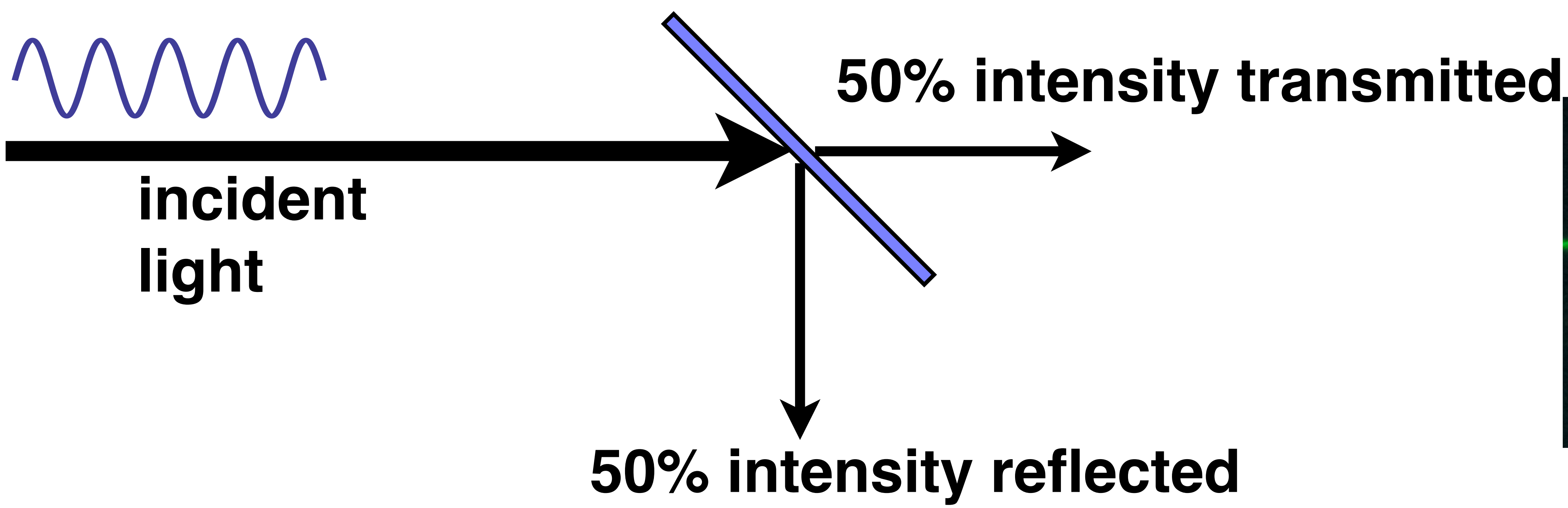
- A classic interference experiment.
- Provides a simpler version of Young's "light-is-a-wave" argument.

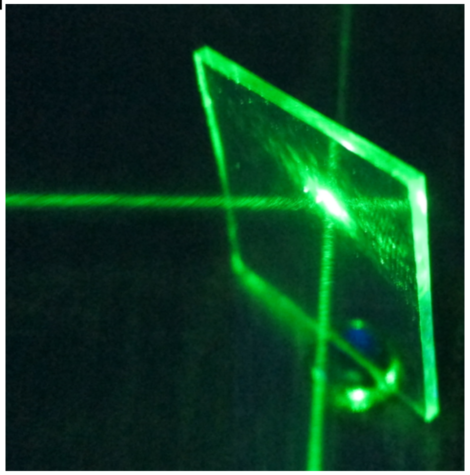


Mach-Zehnder Interferometer

– **Beam splitter -** A “semi-silvered mirror”

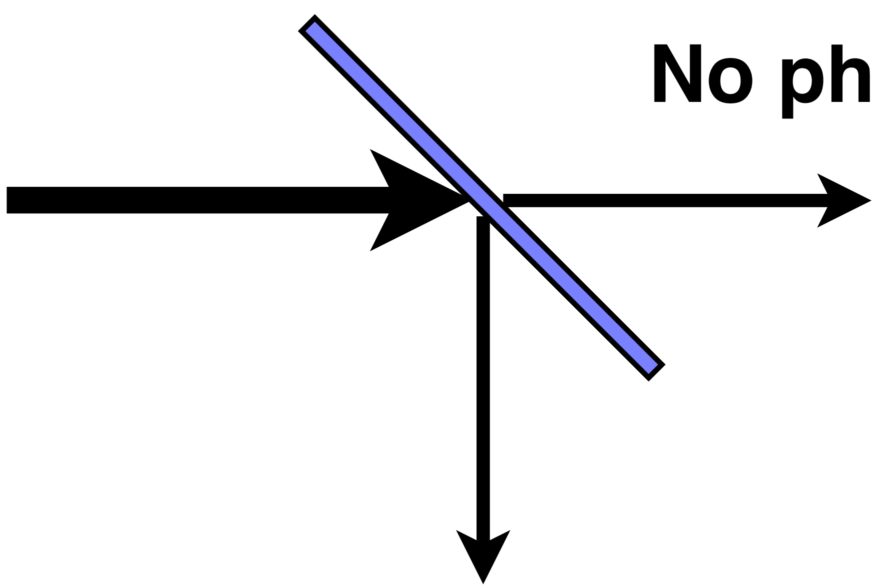
- Most reflecting surfaces reflect **and transmit.**
- A **beam-splitter** is specially tuned **mirror** which transmits 50% of light (**intensity**)
  and reflects 50% of light (**intensity**).

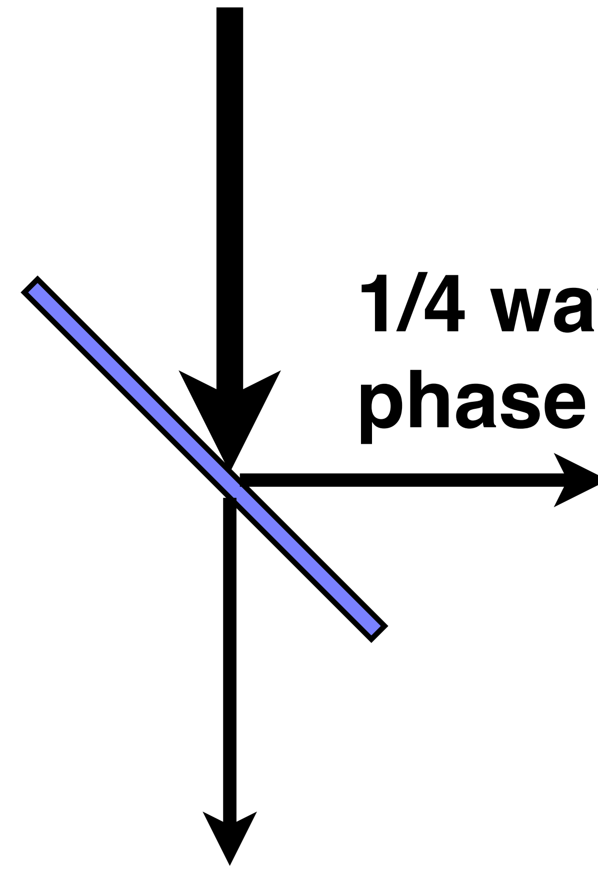




Mach-Zehnder Interferometer

- **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.





Mach-Zehnder Interferometer

–Unsymmetric beam splitter

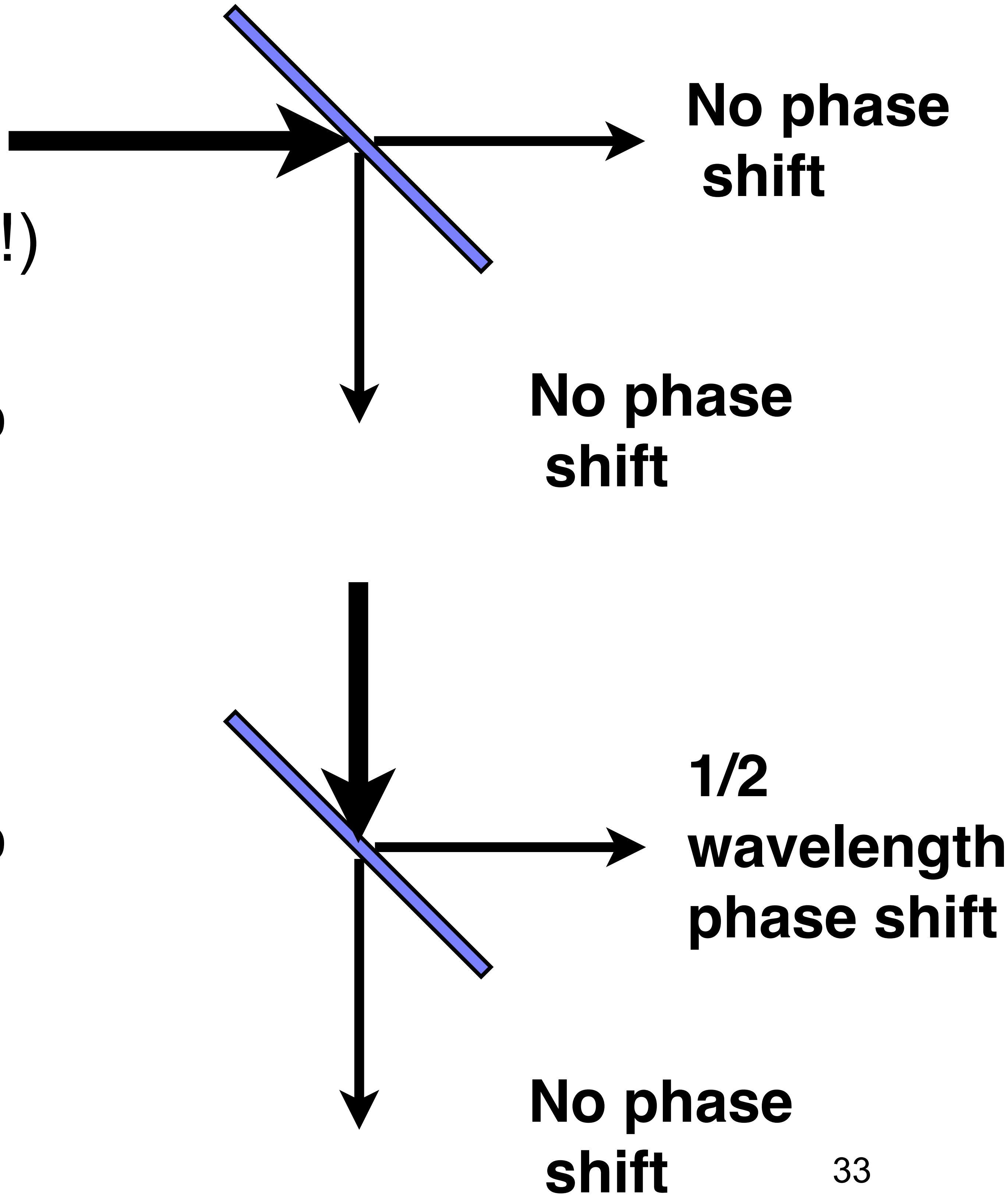
- For information only. Wikipedia (and some school books) use this definition (I wish it didn't!)

–One side

- Transmission causes no phase shift
- Reflection causes no phase shift

–Other side

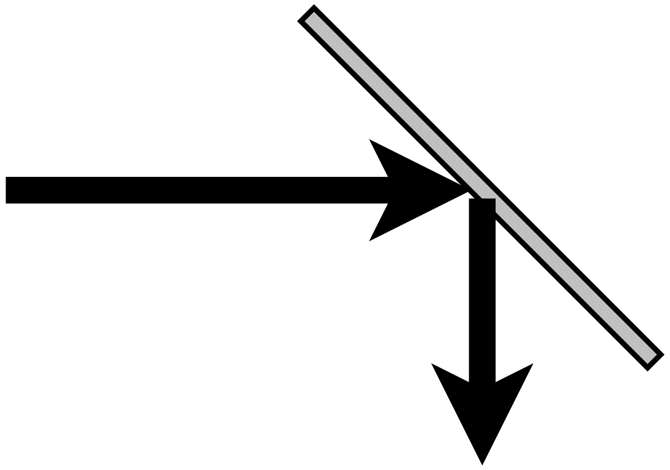
- Transmission causes no phase shift
- Reflection causes 1/2 wavelength phase shift



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.

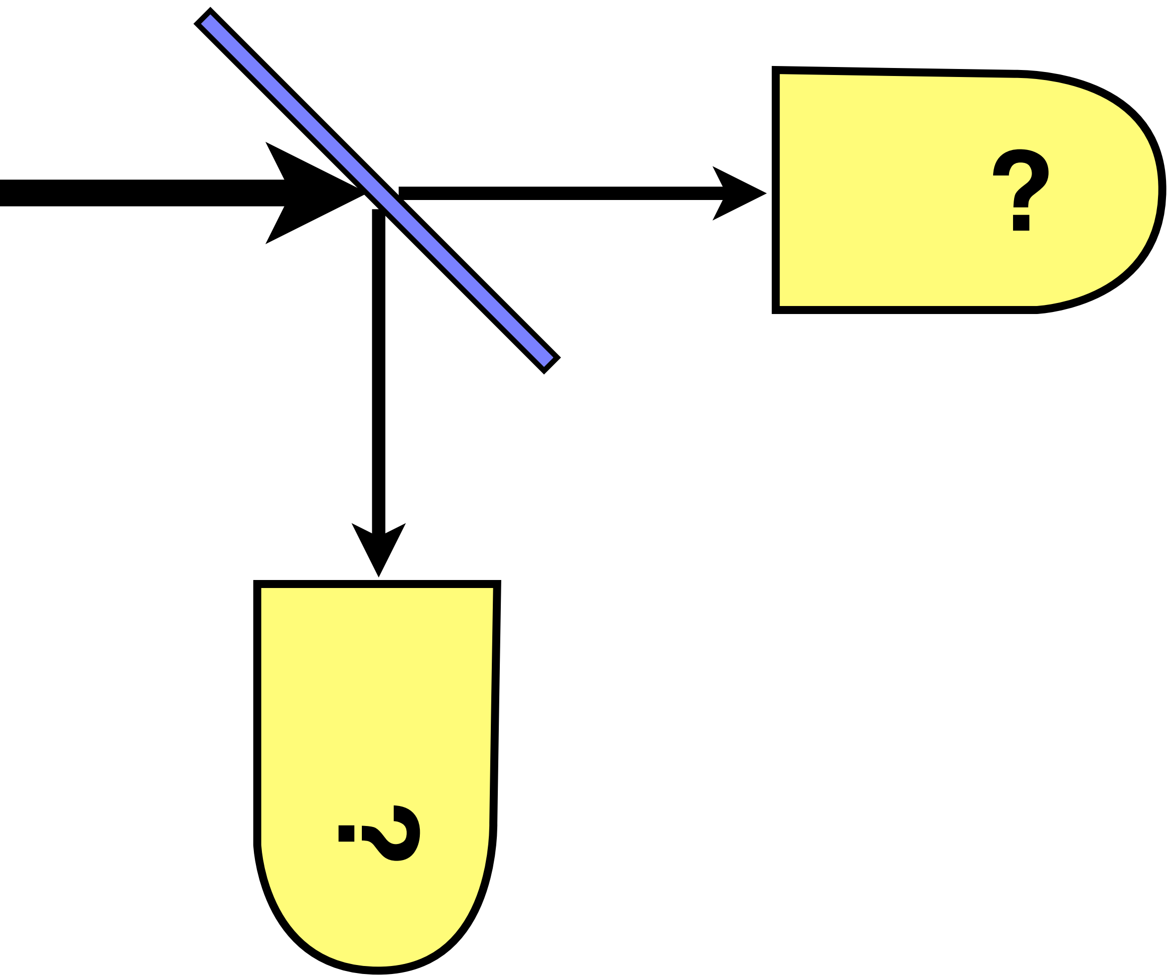


Aside: You get zero phase shift when a wave travelling in a medium with higher refractive index reflects of a boundary with a lower refractive index material (i.e. glass->air) the other way round you get half-wavelength phase shift.

We could use either type of mirror (consistently) and get the same interference effects

Quiz

- Consider a laser beam with power 10W.

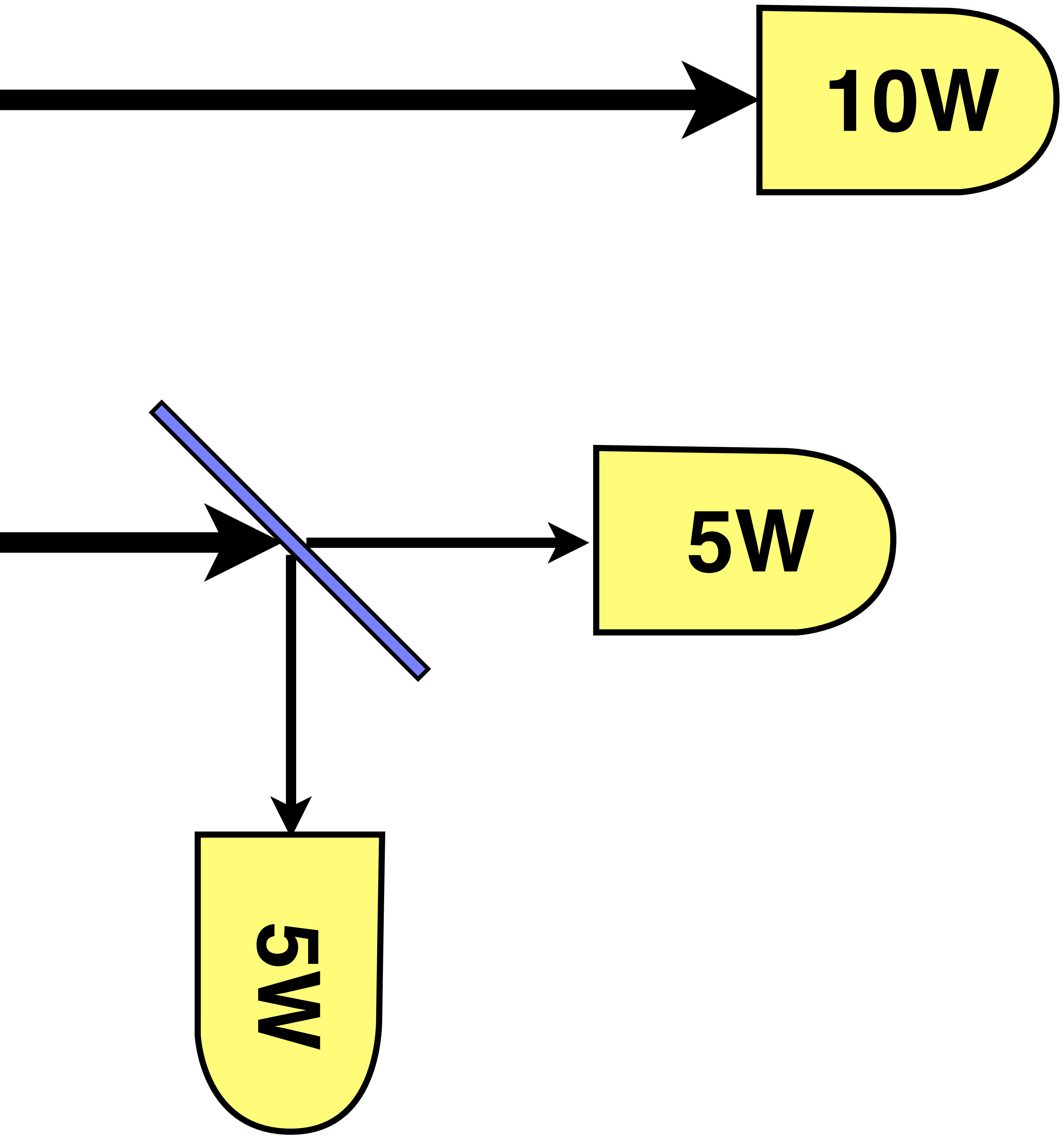


- **We split this beam at a beam splitter. What will the detectors say?**

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

Quiz

- Consider a laser beam with power 10W.



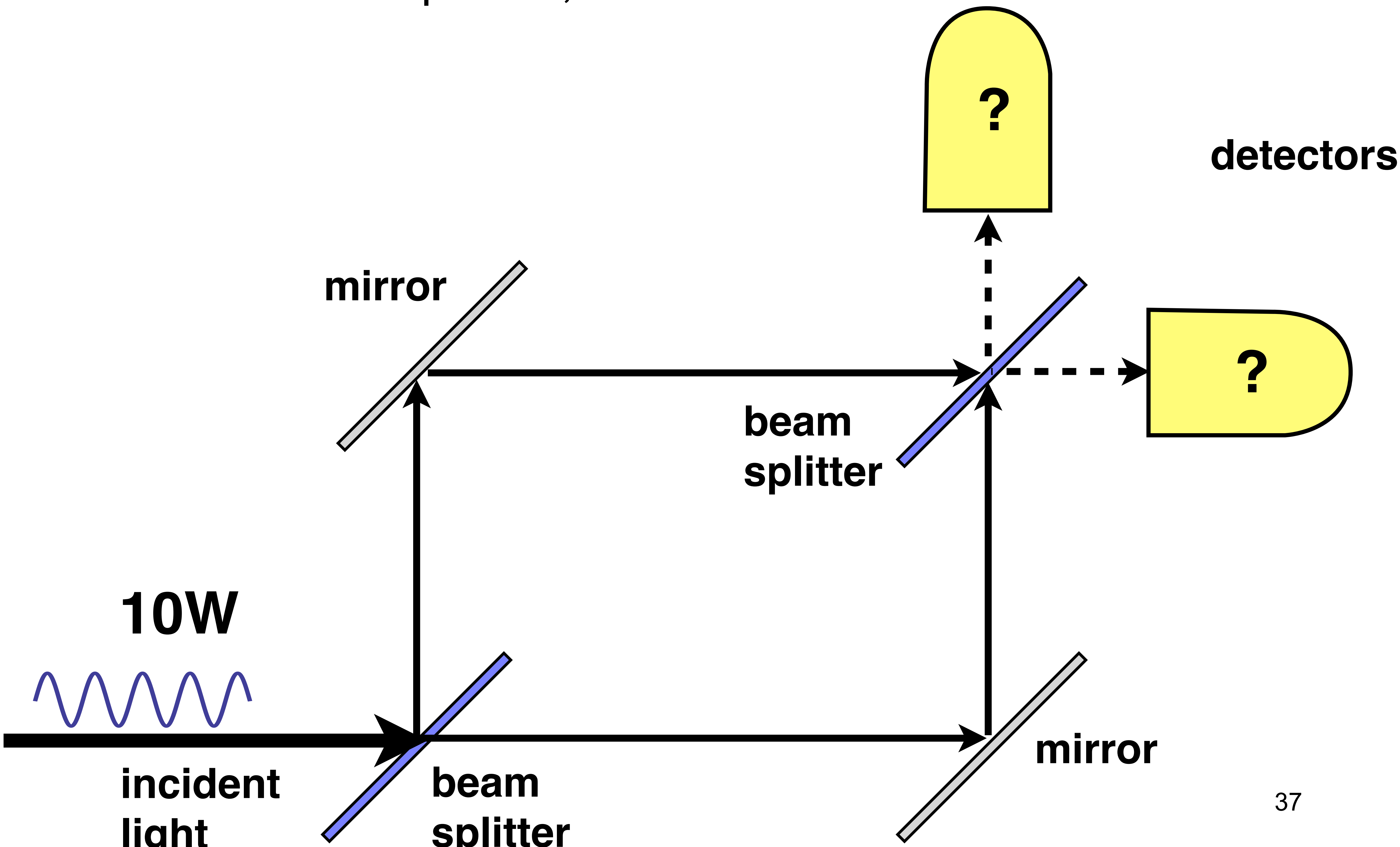
- **We split this beam at a beam splitter. What will the detectors say?**

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

Mach-Zehnder Interferometer

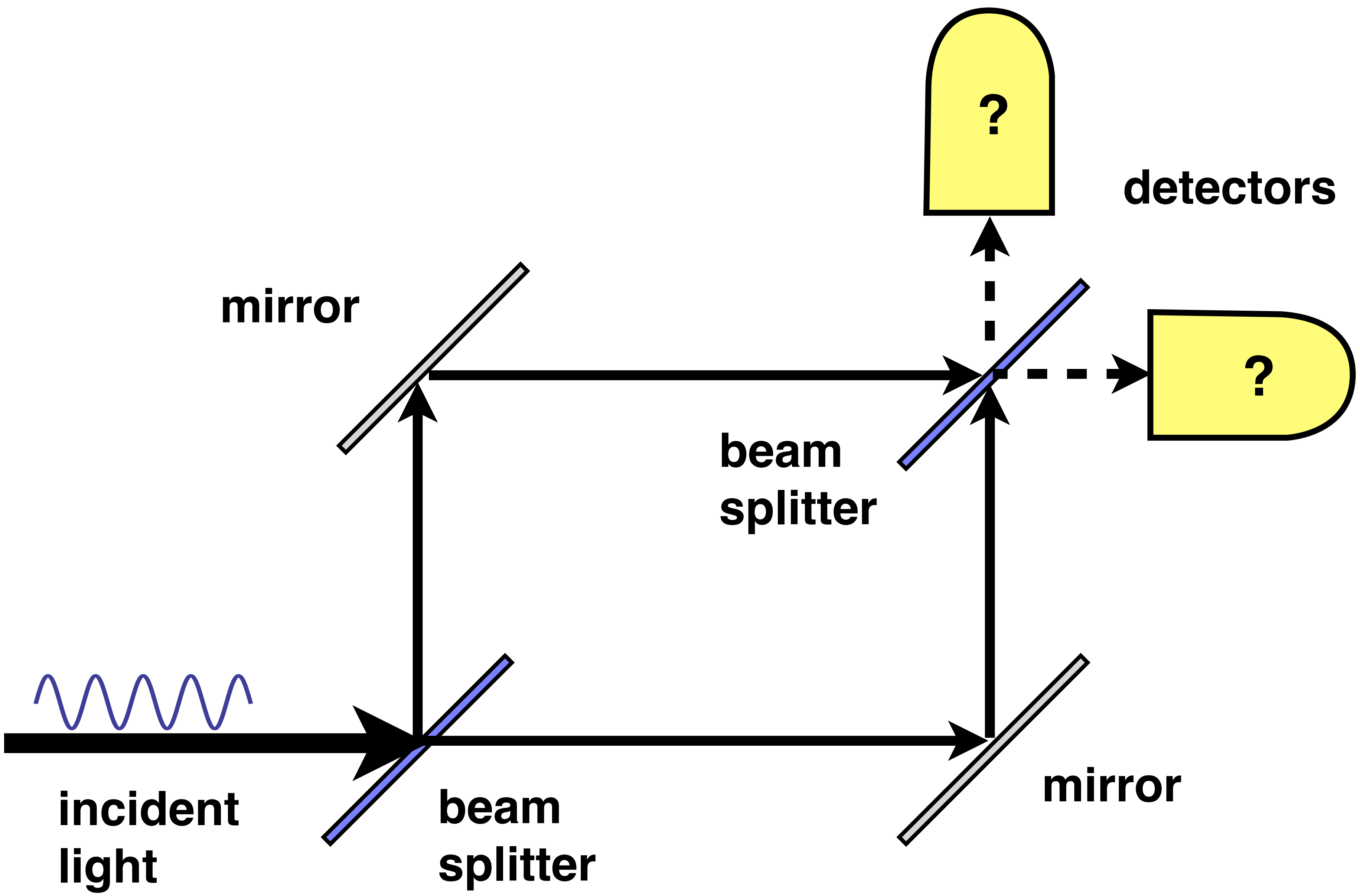
–The **full** Mach-Zehnder Interferometer:

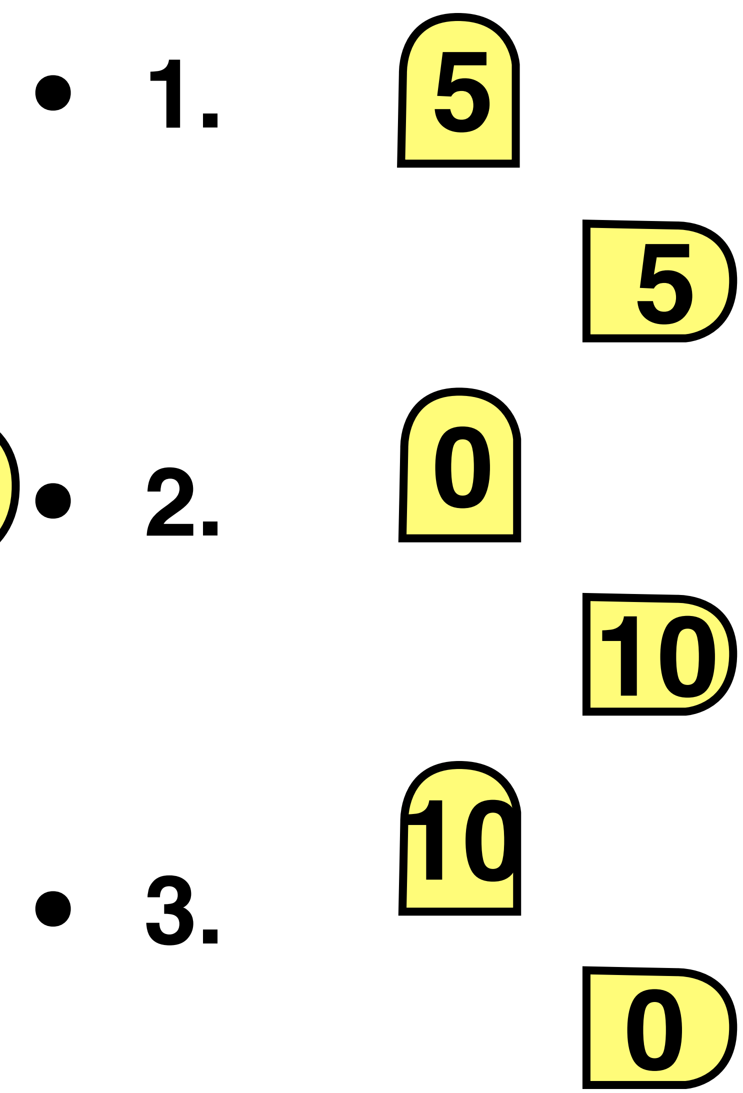
- two beam splitters, two full mirrors and two detectors:



Quiz

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



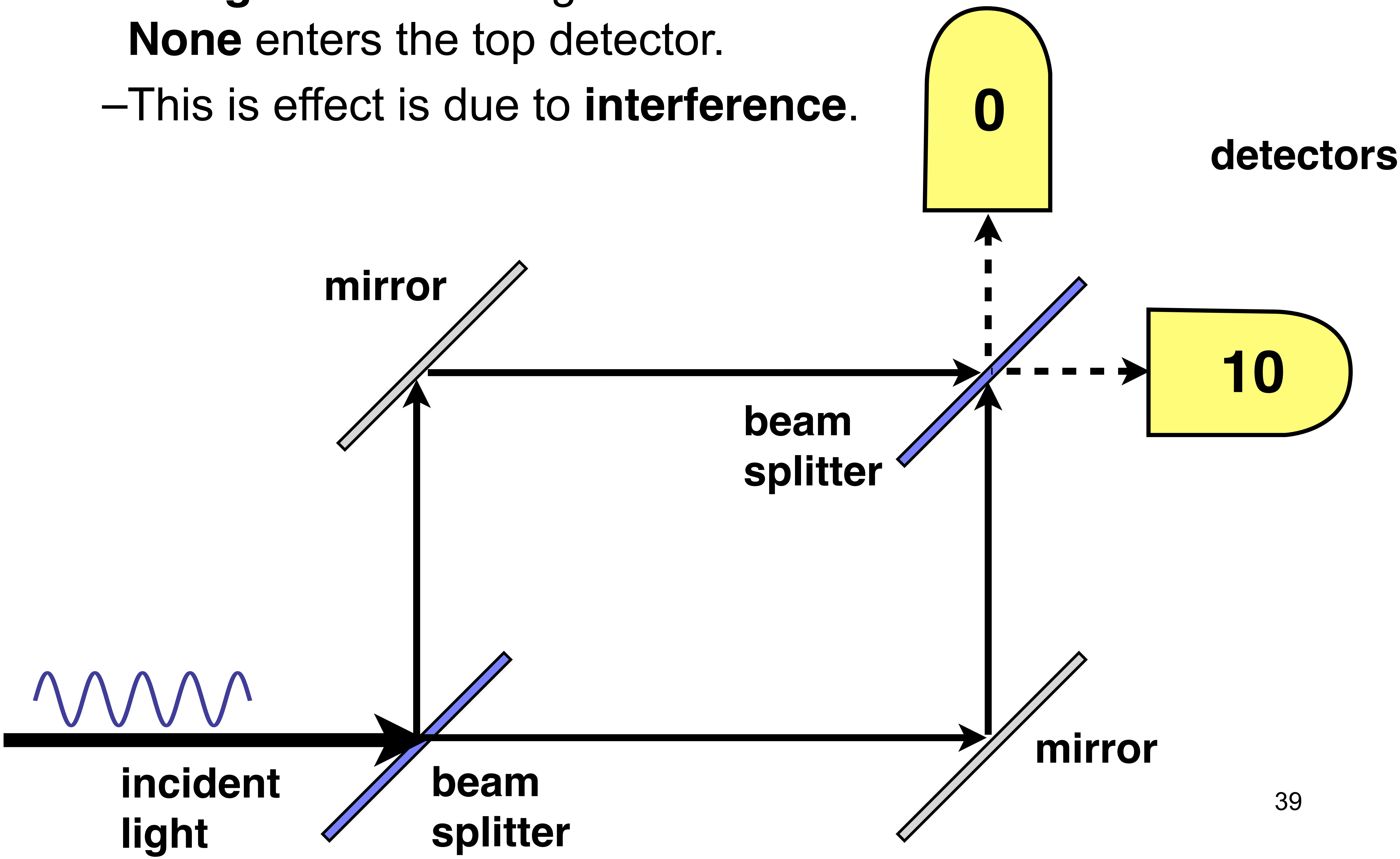


Mach-Zehnder Interferometer

–Option **2** is correct.

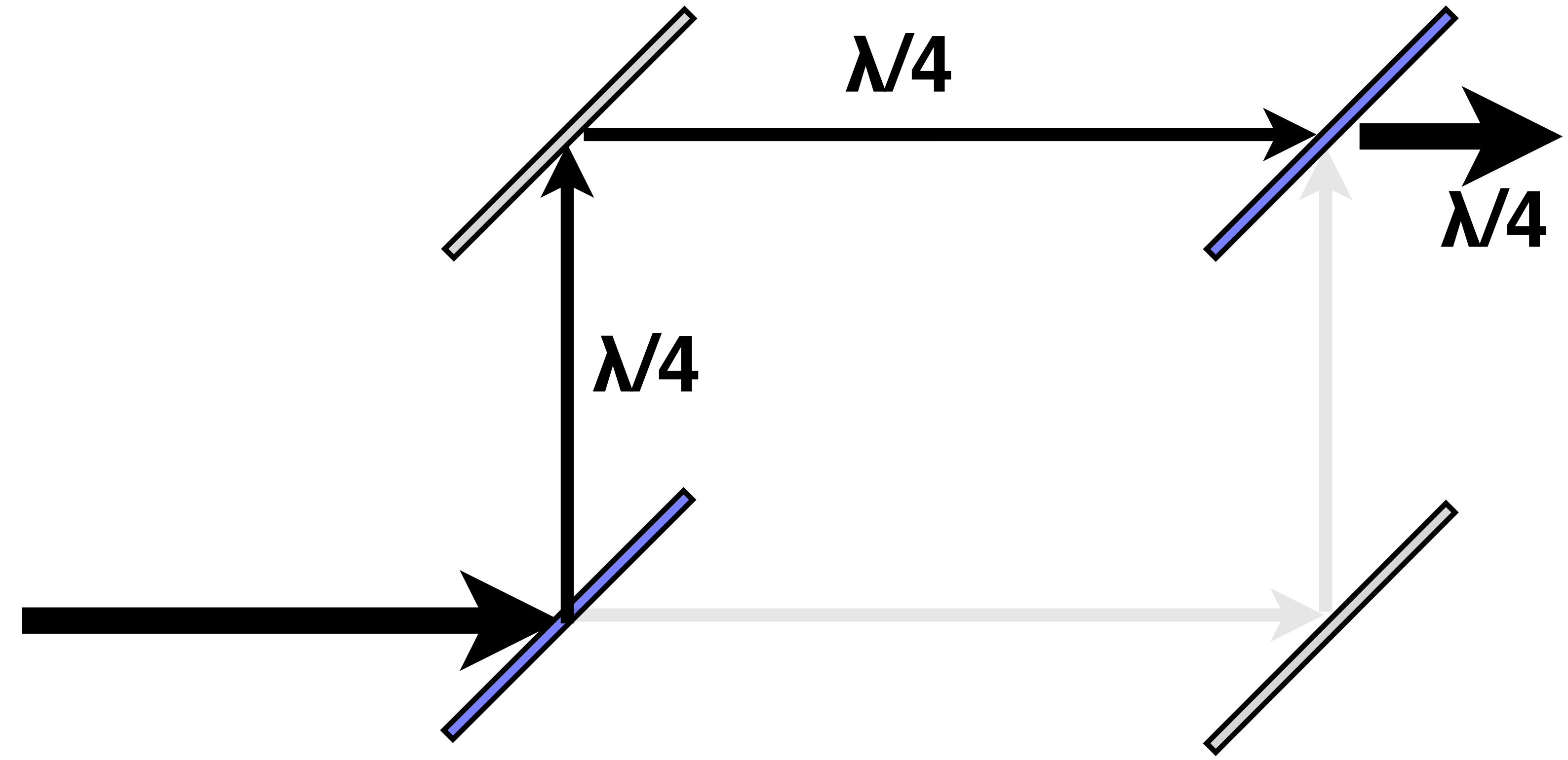
–**All light** enters the right detector.
None enters the top detector.

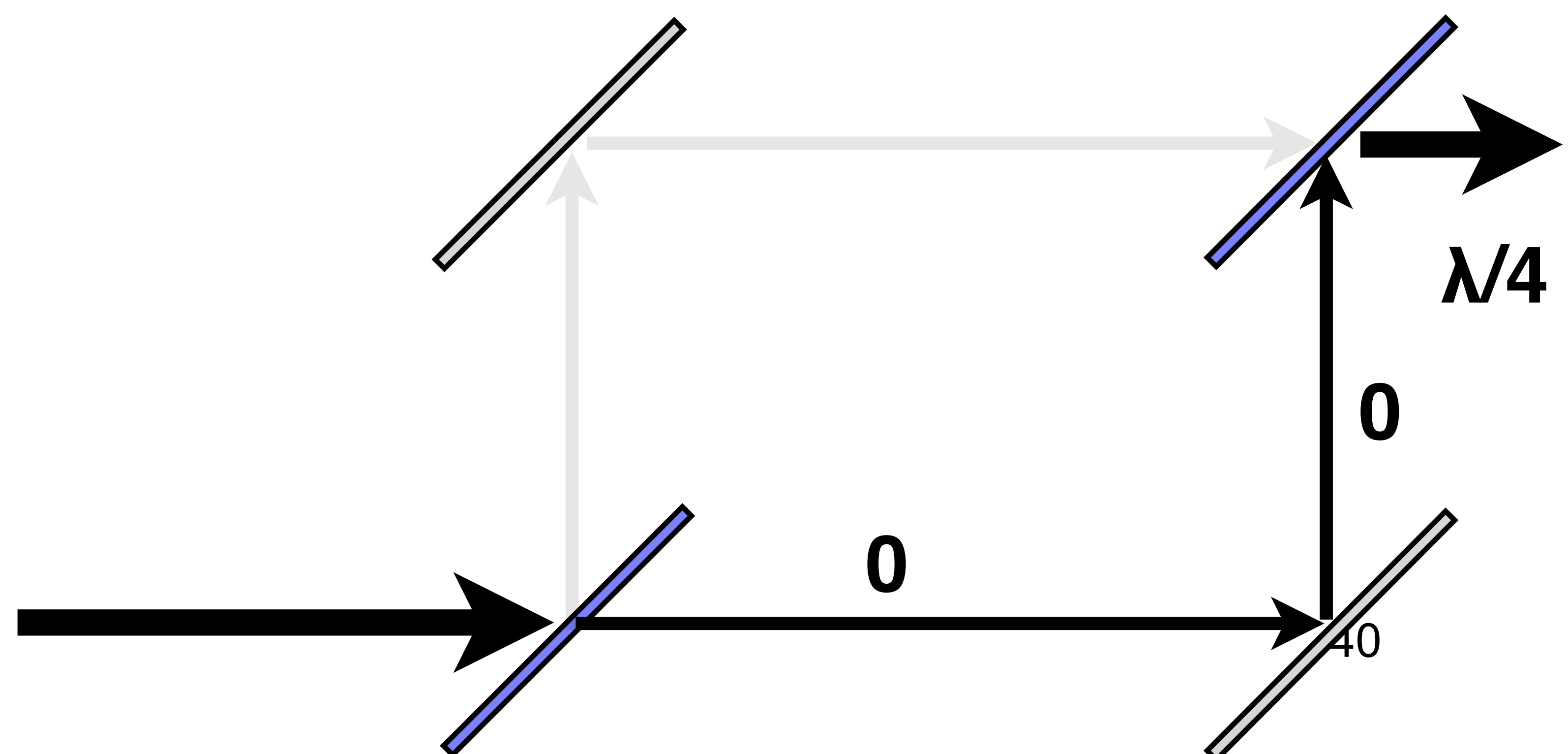
–This is effect is due to **interference**.



Mach-Zehnder Interferometer

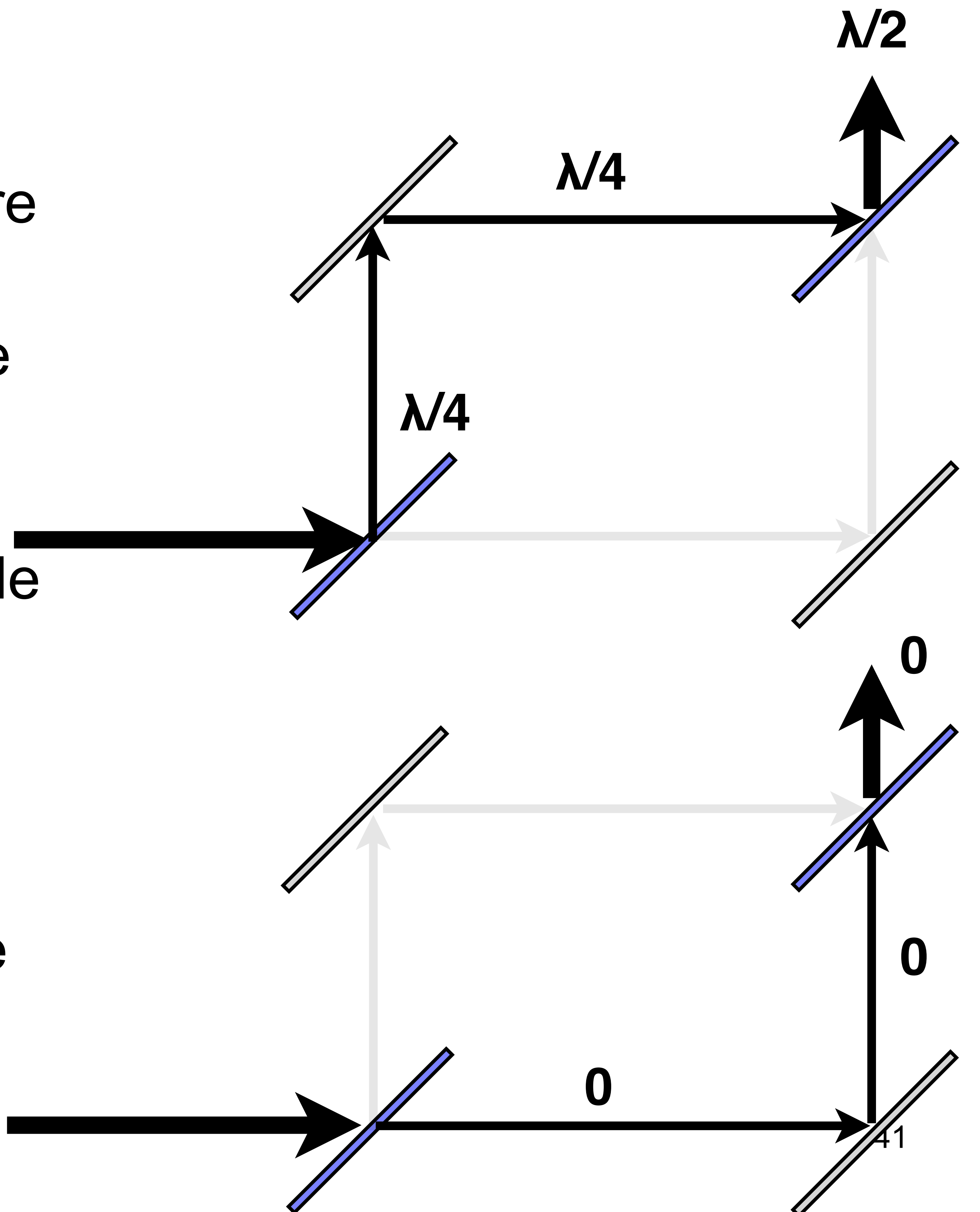
- We can see why by considering the phase shifts on each path.
- First to the **right detector.**
- In both paths, there is **one** reflection (and **one** transmission) **in** a beam splitter.
- The paths have **same** phase shift.
- **In-phase** waves **constructively** interfere.





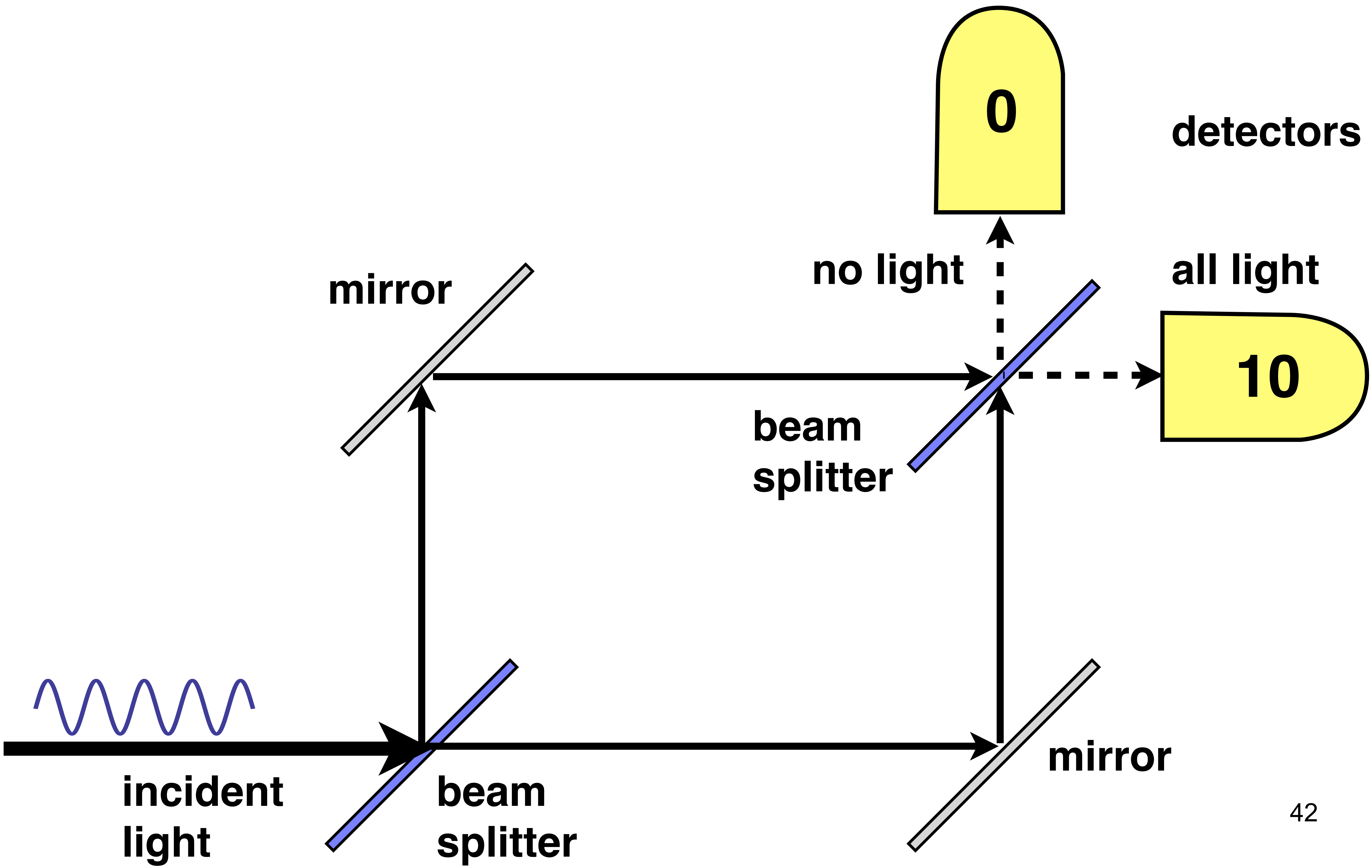
Mach-Zehnder Interferometer

- Now we consider the to the **top detector.**
- In the upper path, there are **two reflections.**
- In the lower path there are **no reflections.**
- The upper path has a phase shift of ***λ/2*,** while the lower 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.

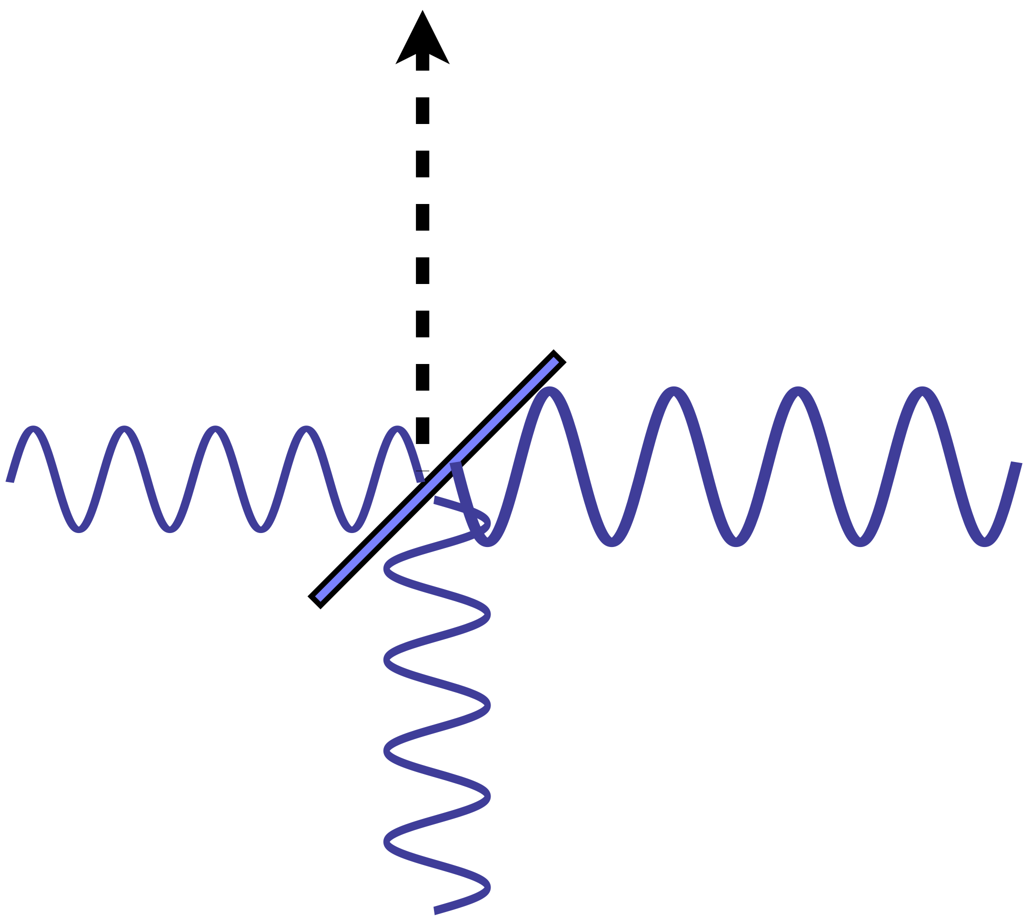


Aside: Conservation of Energy

- Physicists like **conservation of energy**… it is **inviolate**
  - –Because that is the way nature seems to work
- This means that **interference effects** can not change the **total** amount of light, they can just **move** it around
- This is true in the **double slit** experiment where with both slits open there is twice as much light (**intensity**) as with the single slit, but the **interference** effects move the light to make the **fringe** pattern.
- So what happened to the light that would have travelled to the **top** detector?

Conservation of energy

The two incoming waves at the last beam splitter **destructively interfere** on the **top** path … where does this **energy** go?



The **energy** ends up in the **right** hand path in the form of **constructive interference**

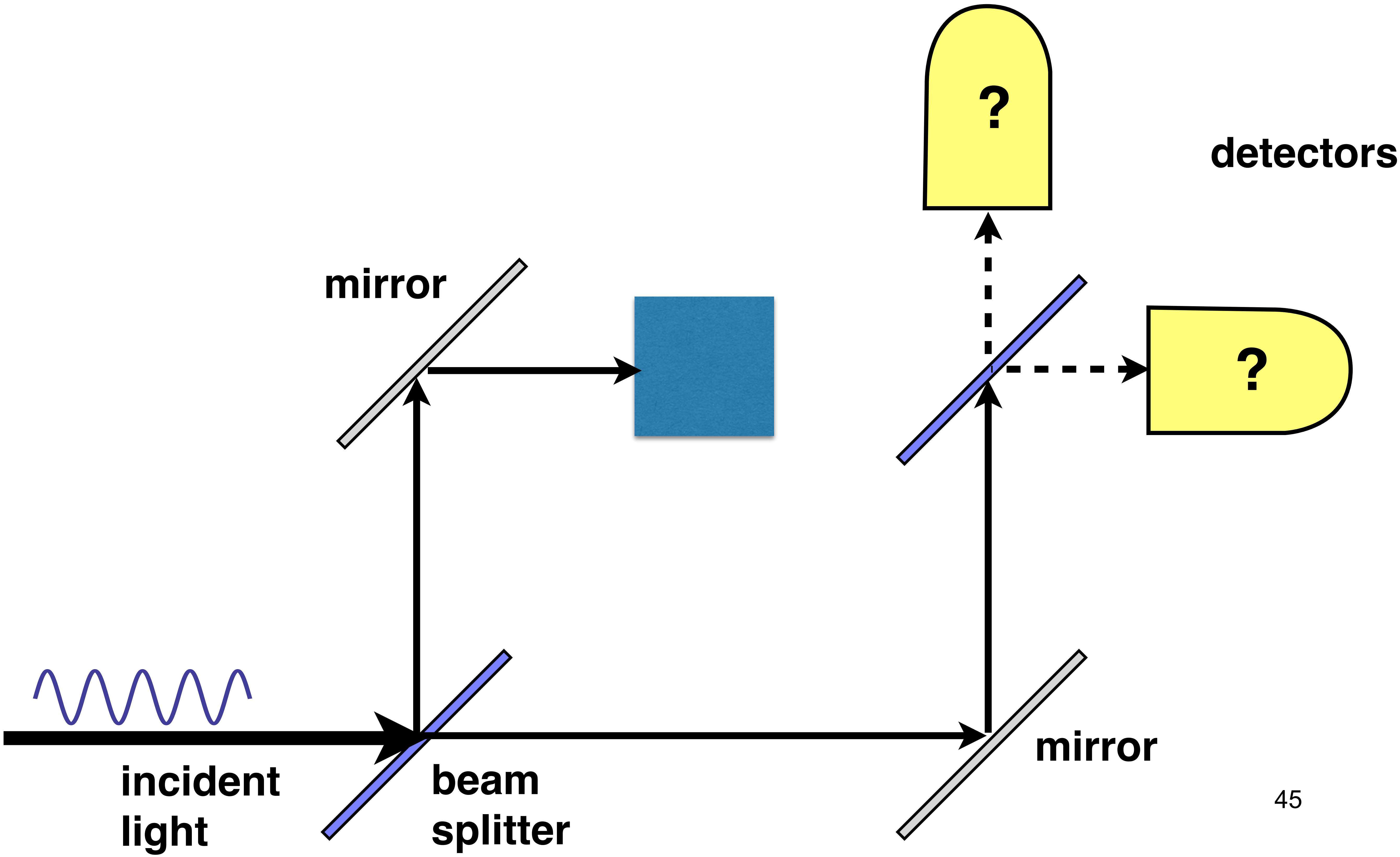
You could **almost** think about each wave in the top path providing a reflection that blocks the other wave from travelling down the top path forcing all the energy to travel down the right path…

… but things get weirder so don't put too much store in the classical picture.

Mach-Zehnder Interferometer

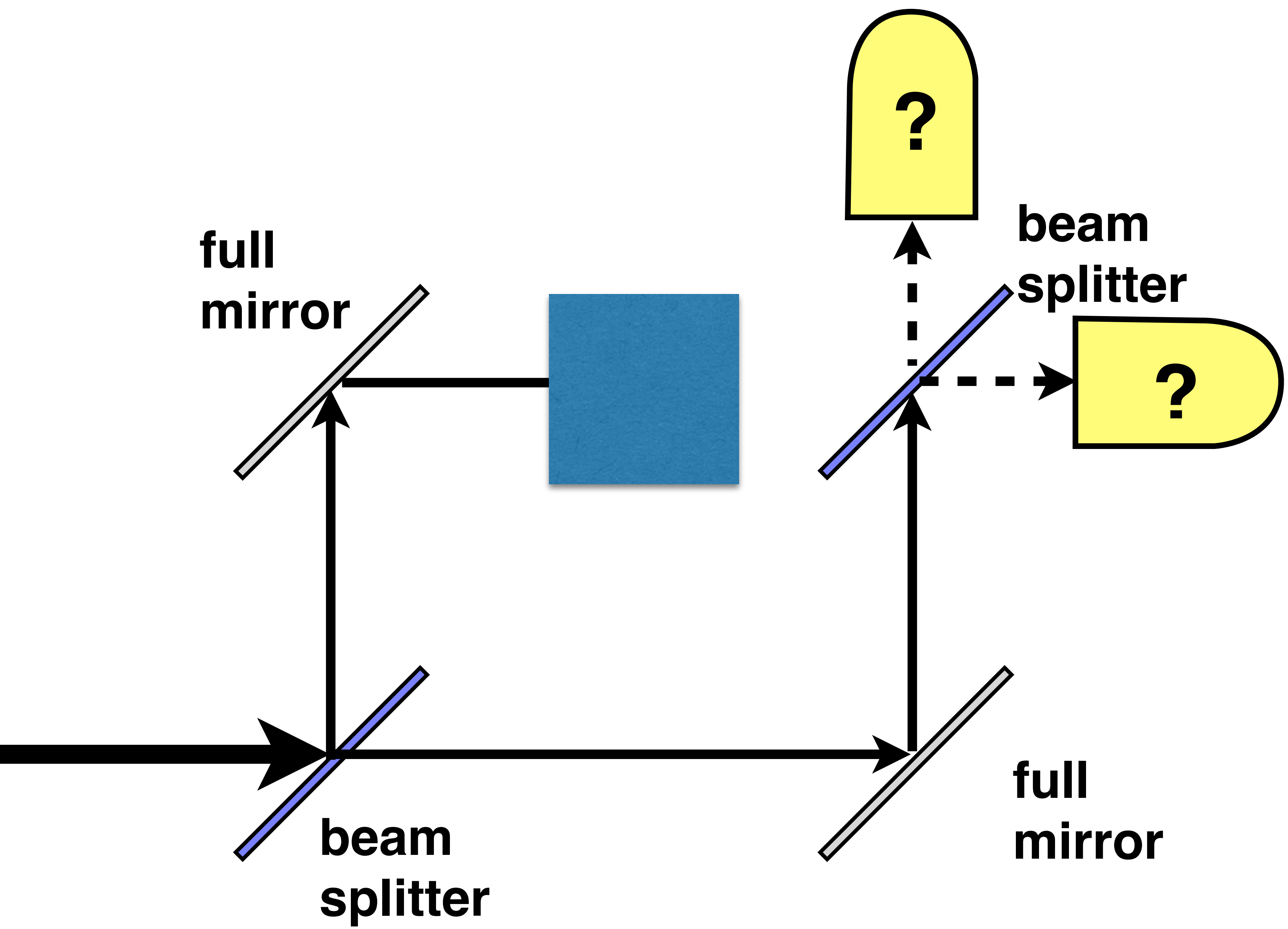
–A particle picture cannot explain this.

–Consider if we **block** one of the arms:

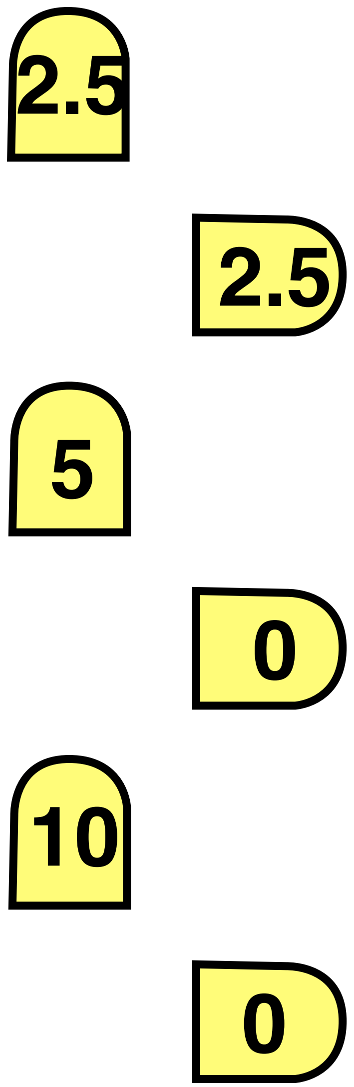


Quiz

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

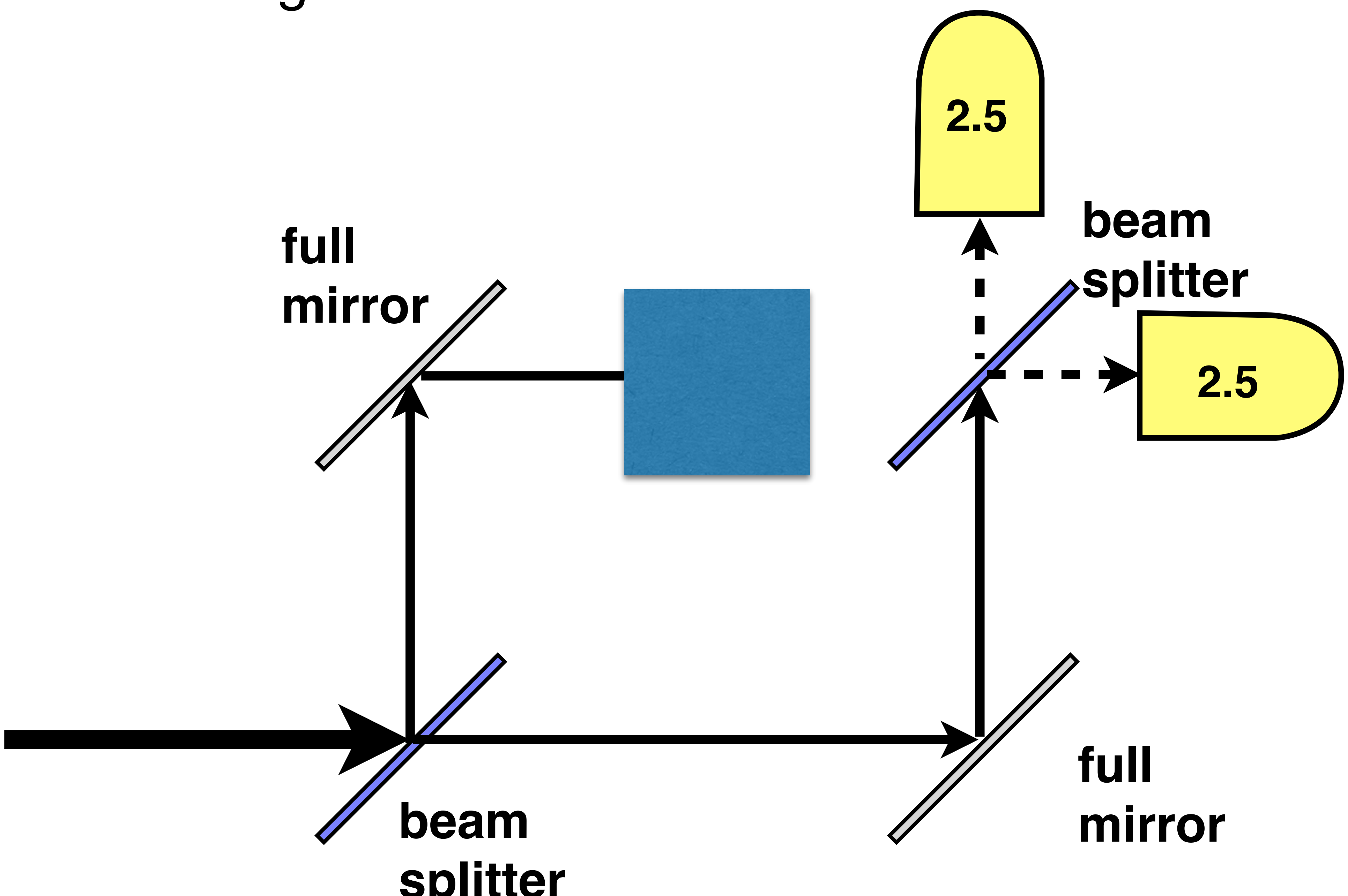


- 1.
- 2.
- 3.



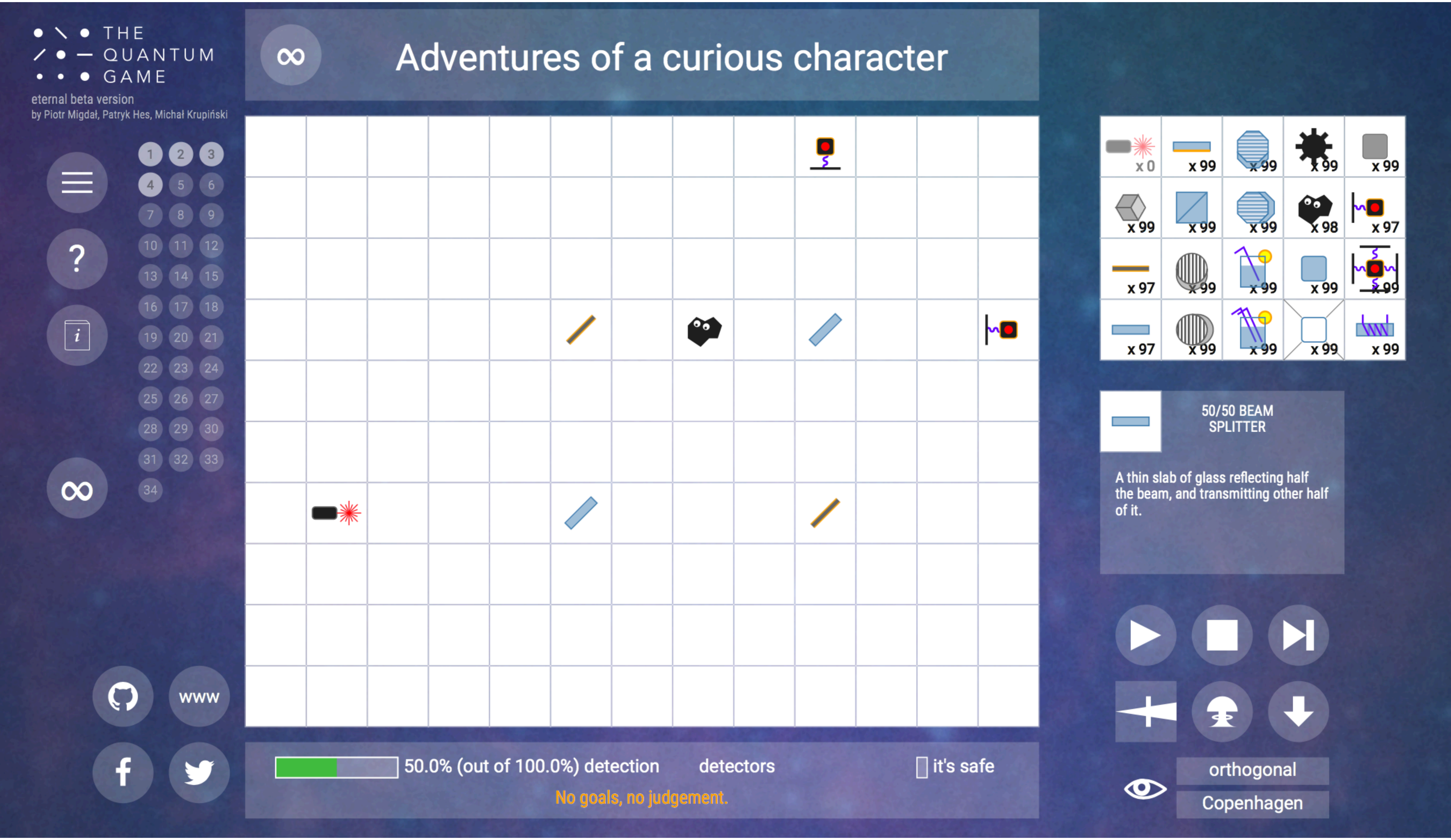
Mach-Zehnder Interferometer

- 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.



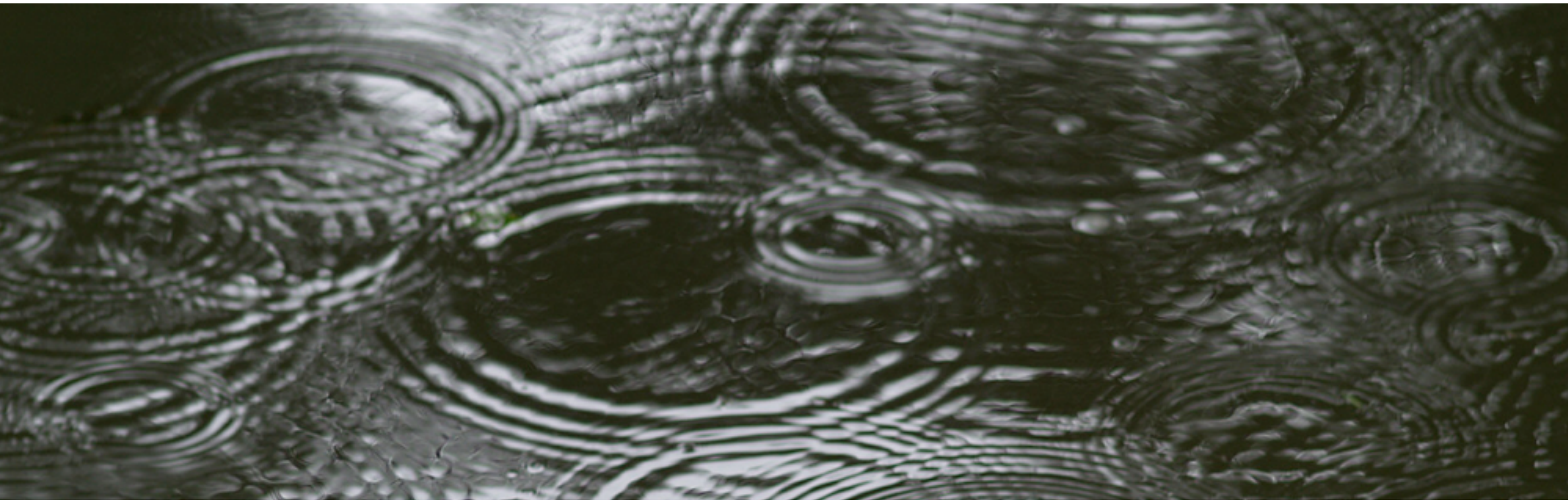
Game time

- http://quantumgame.io



Problems with the wave picture

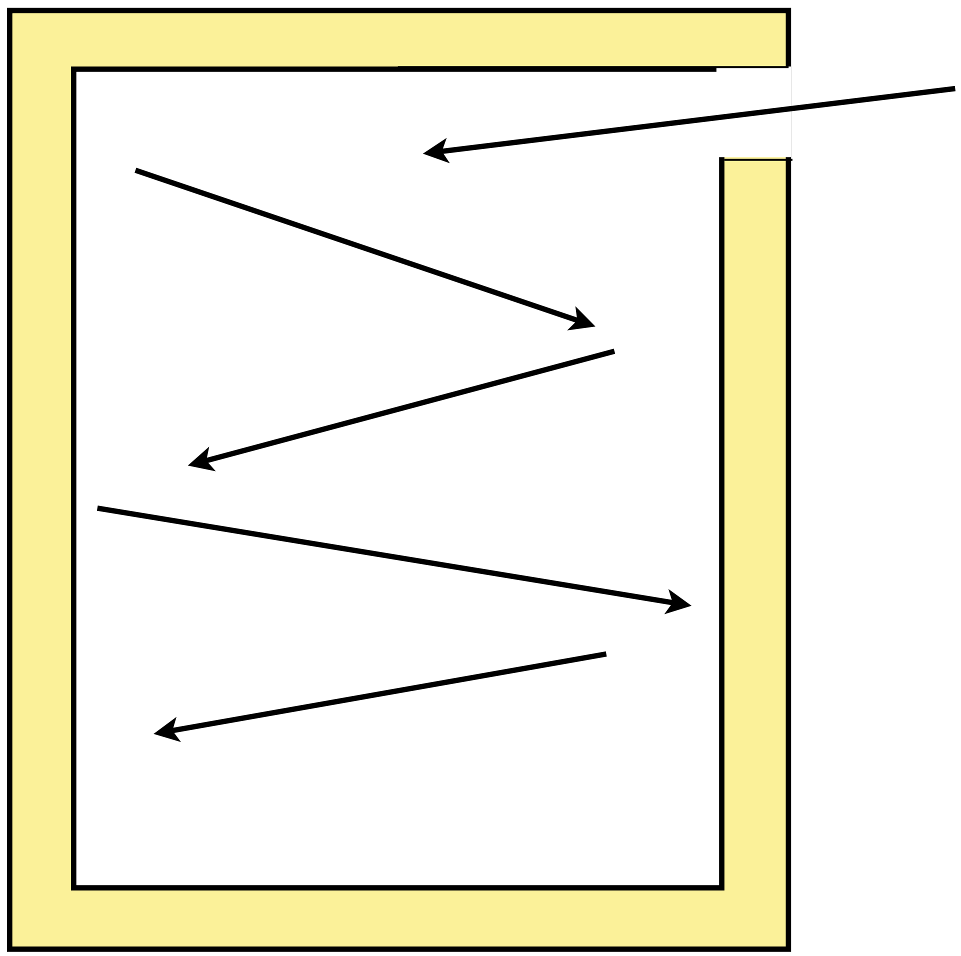
- The Young double slit experiment and the Mach-Zehnder both seem **irrefutable evidence** that **light** is a **wave**.



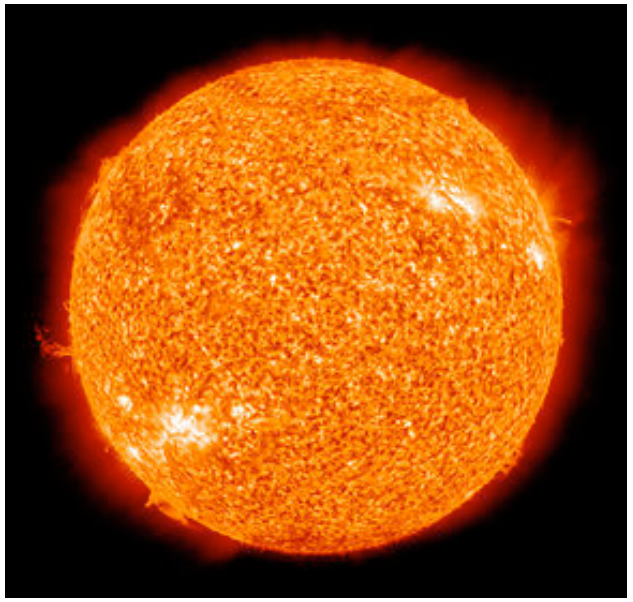
Black-body radiation

–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

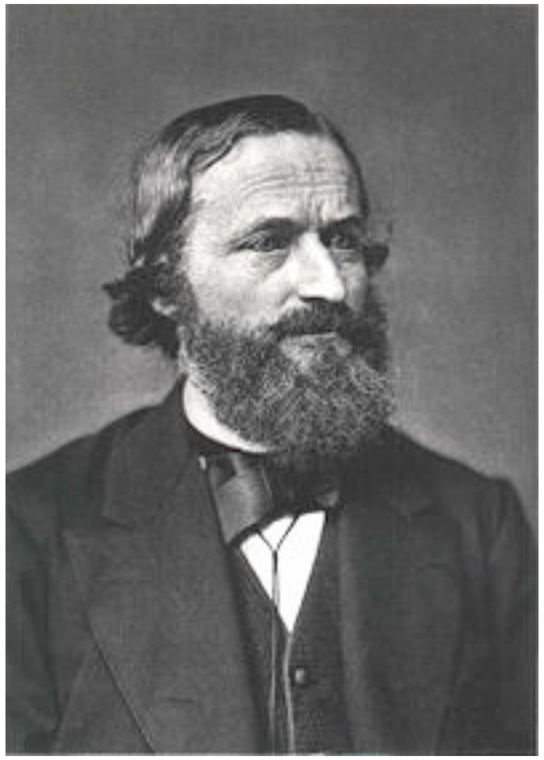


- **Although an idealisation, many physical objects behave approximately like a black body.**

Black-body radiation

- 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!

Gustav Kirchoff



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

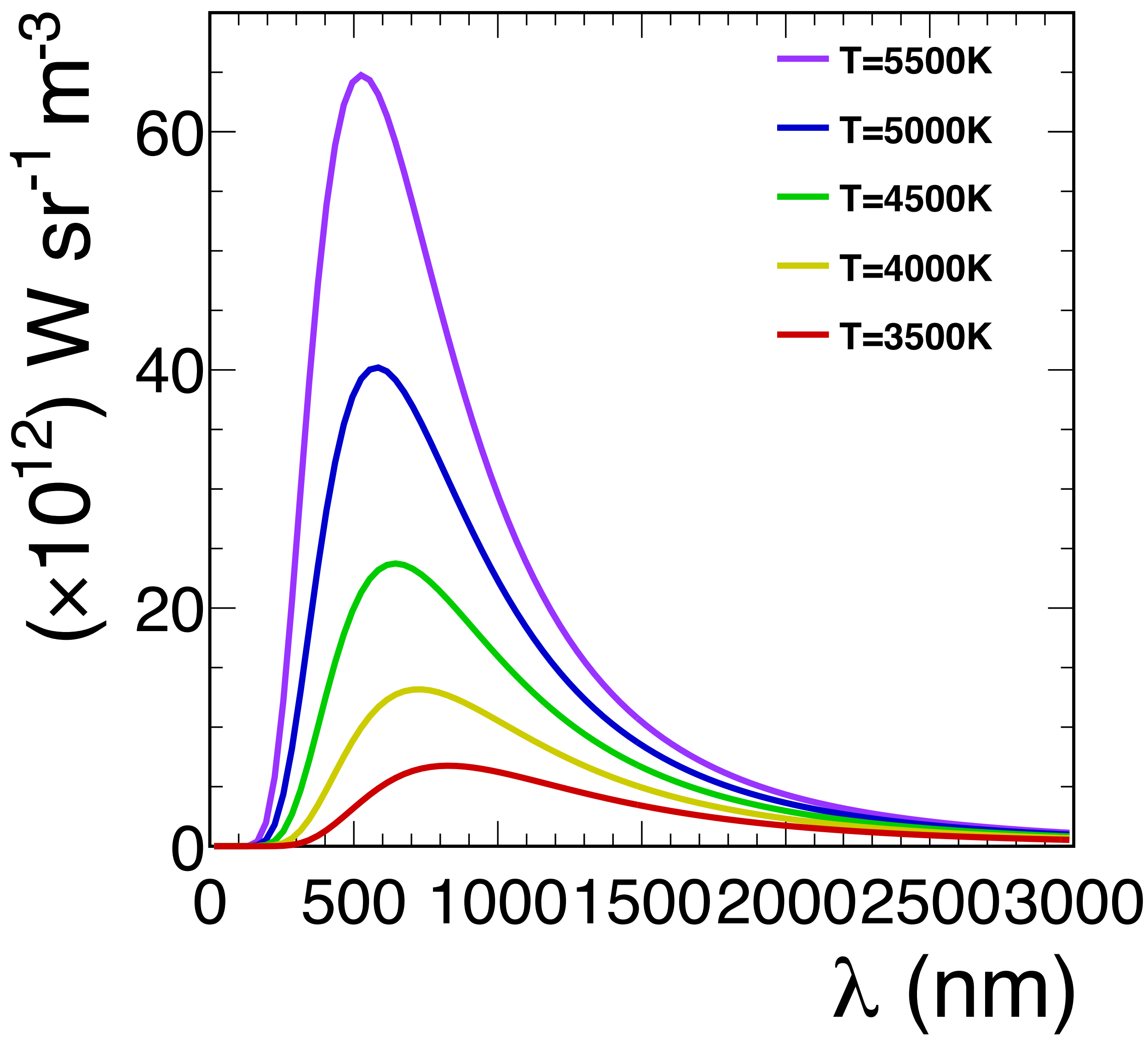
- Still used by astronomers (will feature in second half of this course).

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

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

Black-body emission spectra



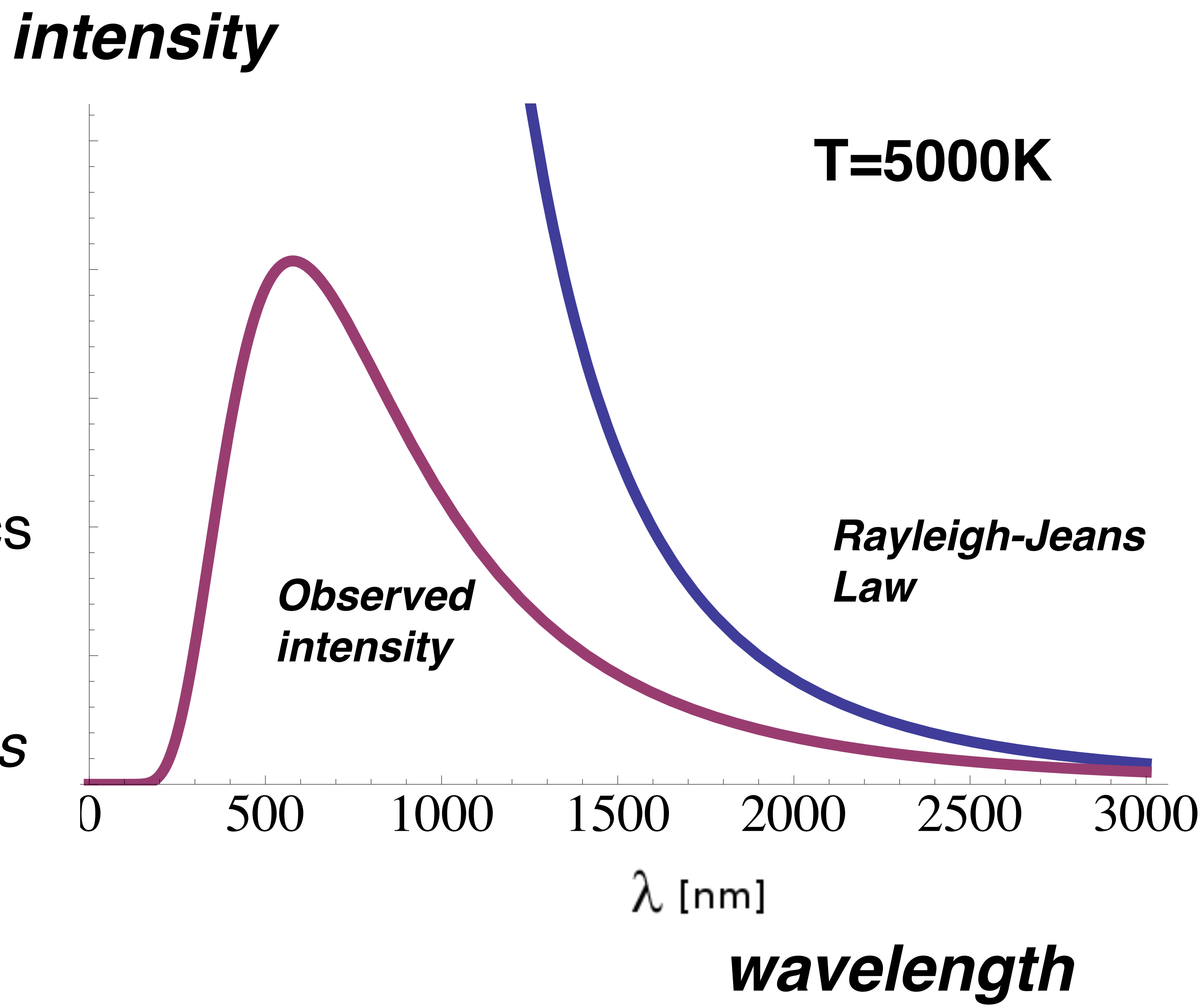
wavelength

Black-body radiation

- Aim: A theoretical derivation of these curves.
- Best attempt: **Rayleigh-Jeans law**

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

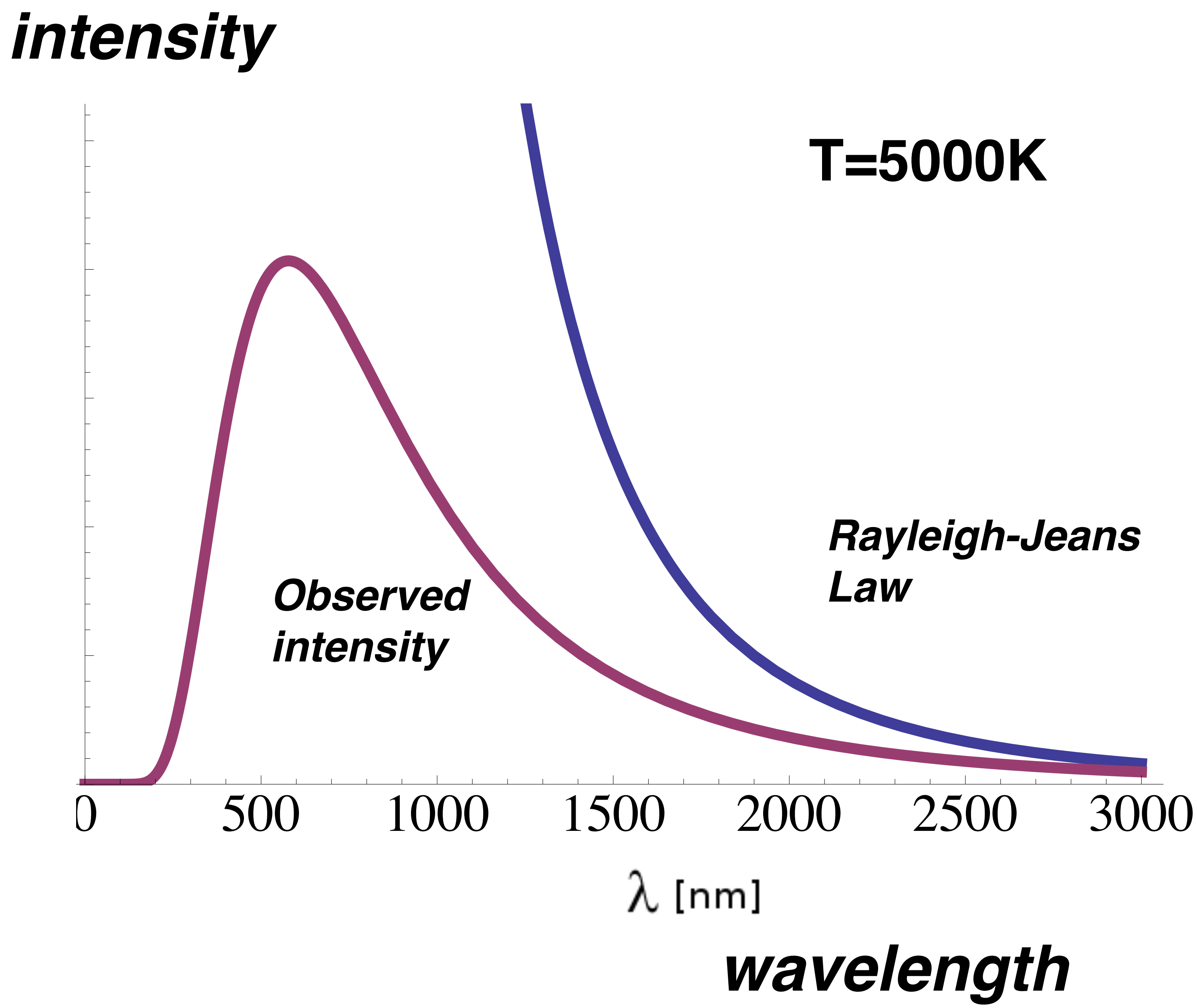
  - **c** is the speed of light, **k** is Boltzmann's constant, **T** is temperature, and **λ** is wavelength
- Derivation used thermodynamics and wave model of light. *(See 2nd year Statistical Thermodynamics course).*
  - Key assumption - at all wavelengths light energy is absorbed and emitted **continuously**.



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.

$$E = hf$$

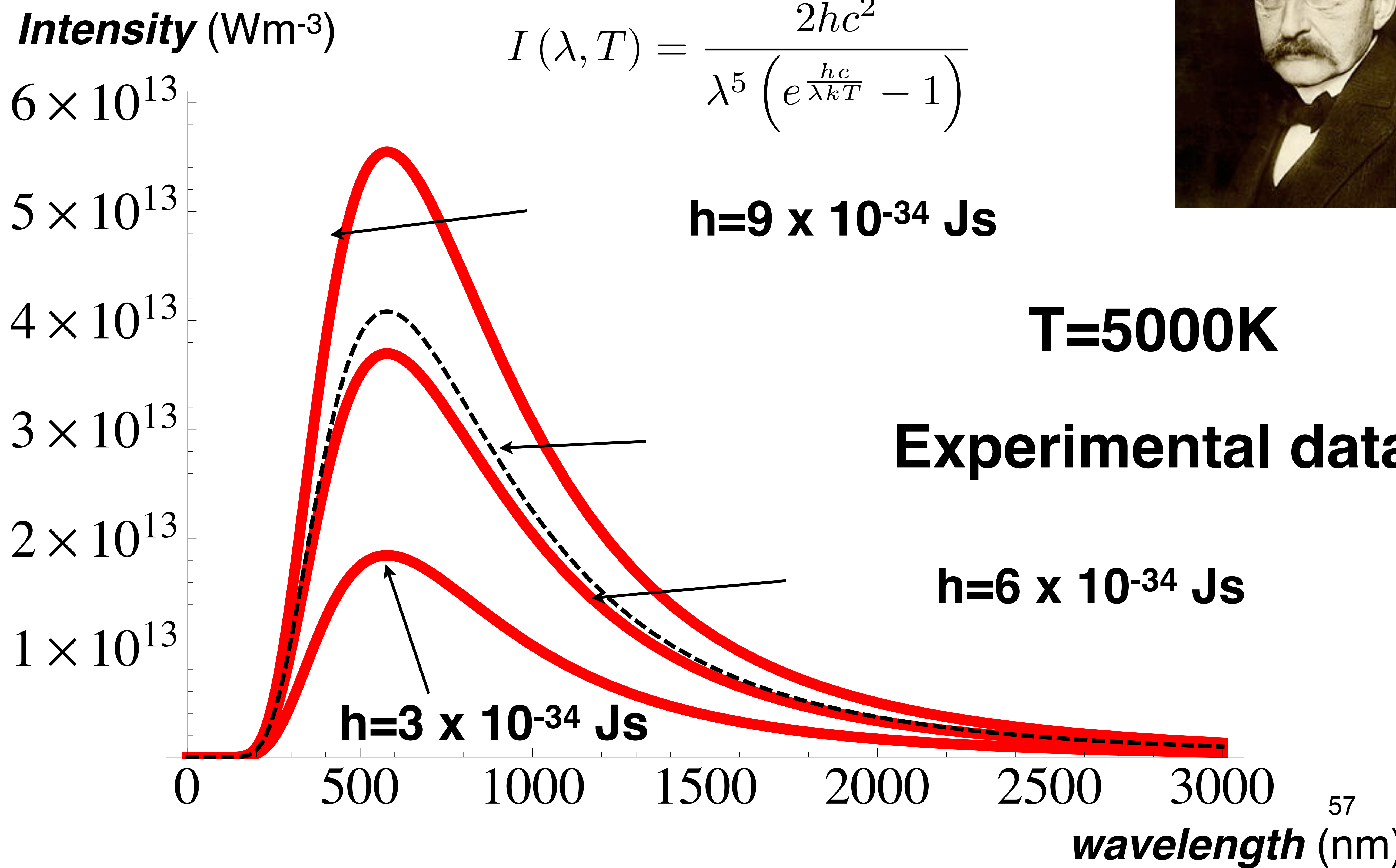
    - where ***f*** is **frequency** and **h** is a constant **to be determined**
  - The result: **Planck's law** (derived in 2nd year Thermal Physics)

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5 \left(e^{\frac{hc}{\lambda k T}} - 1\right)}$$

Black-body radiation

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

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5 \left(e^{\frac{hc}{\lambda k T}} - 1 \right)}$$



Black-body radiation

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

$$h = 6.626070040 \times 10^{-34} Js$$
$$\pm 0.000000081 \times 10^{-34} Js$$

  - –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

Planck constant from http://physics.nist.gov/cgi-bin/cuu/Value?h

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.

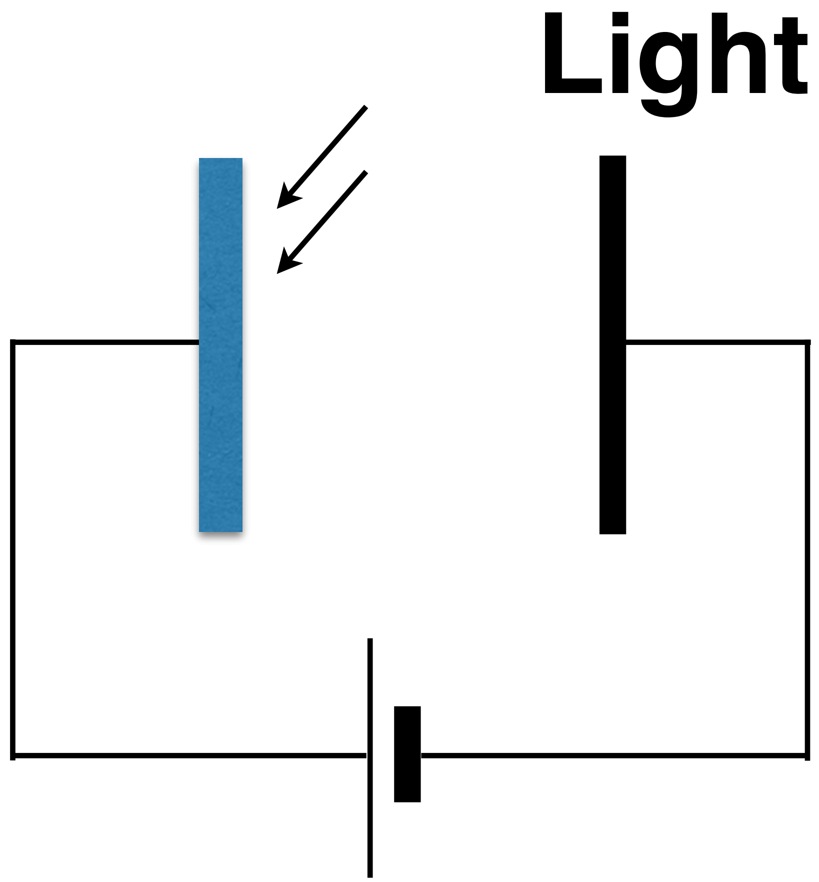
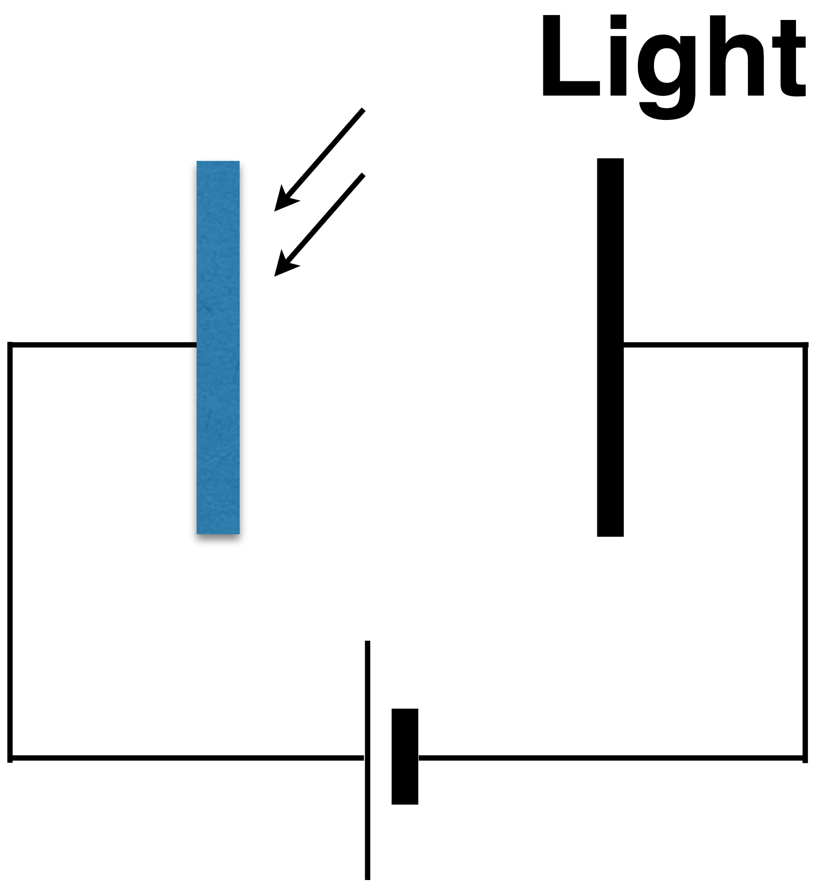
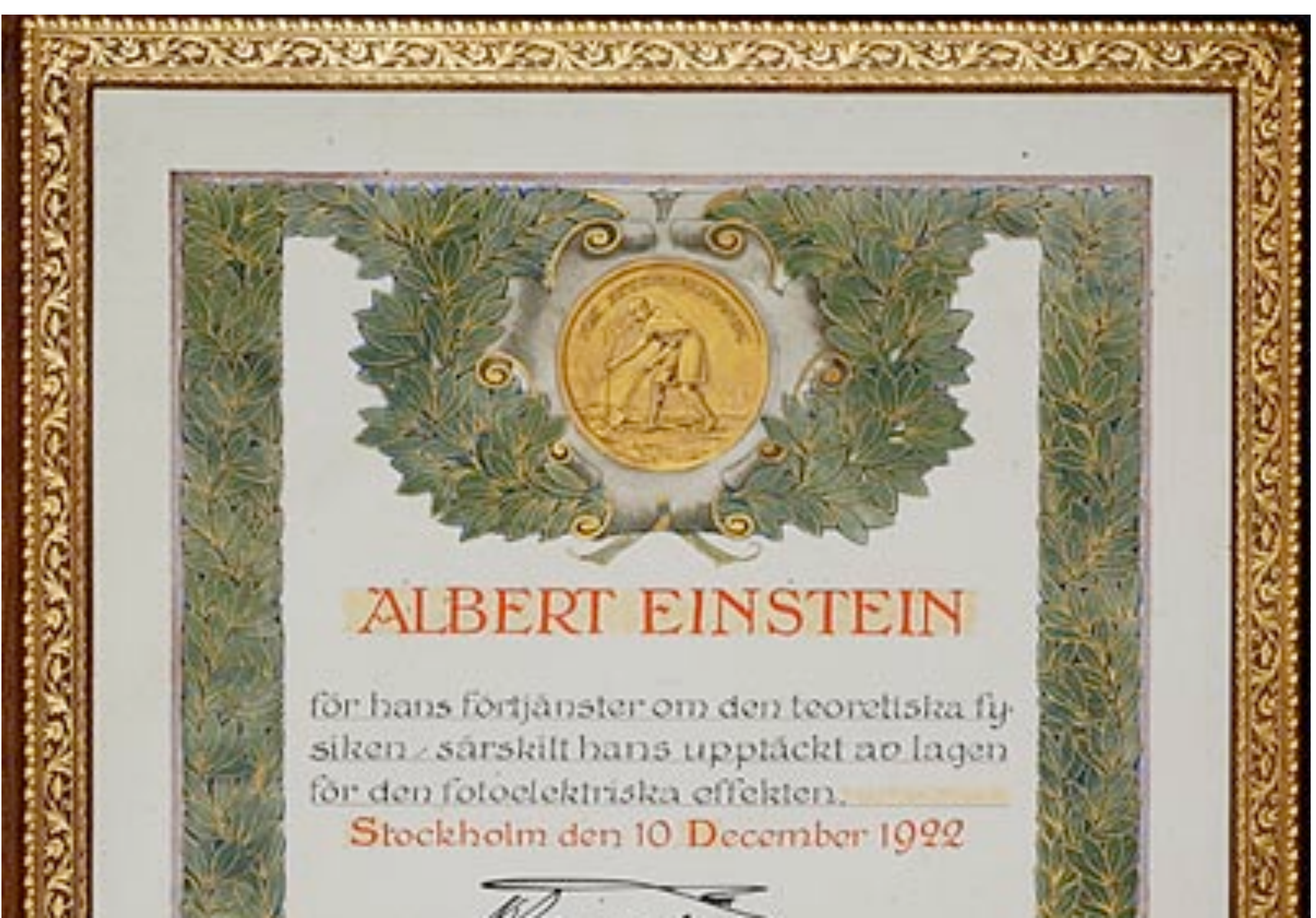


Photo-electric effect





- 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.

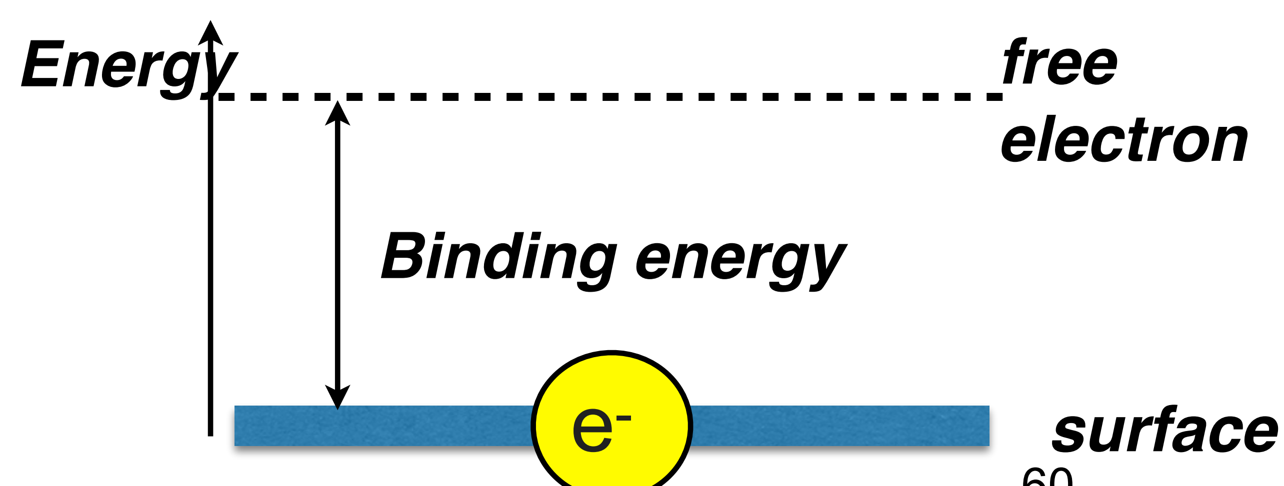
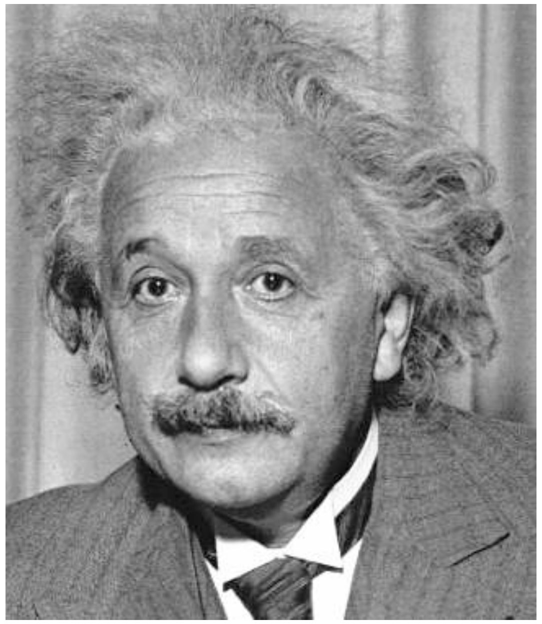


Photo-electric effect

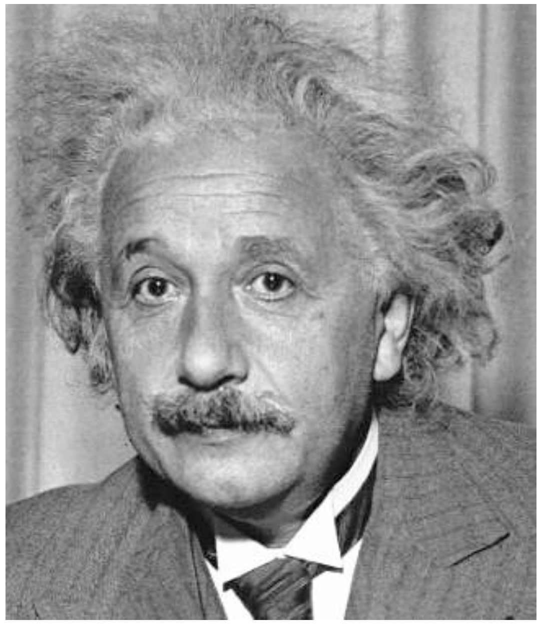


- Einstein's model explained **all** features of the photo-electric effect.
- But could the **wave picture** of light be given up so readily?
- But Young's **wave evidence** was **very strong**. Perhaps the photo-electric effect had **another explanation**?
- To convince the bulk of physicists more **persuasive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

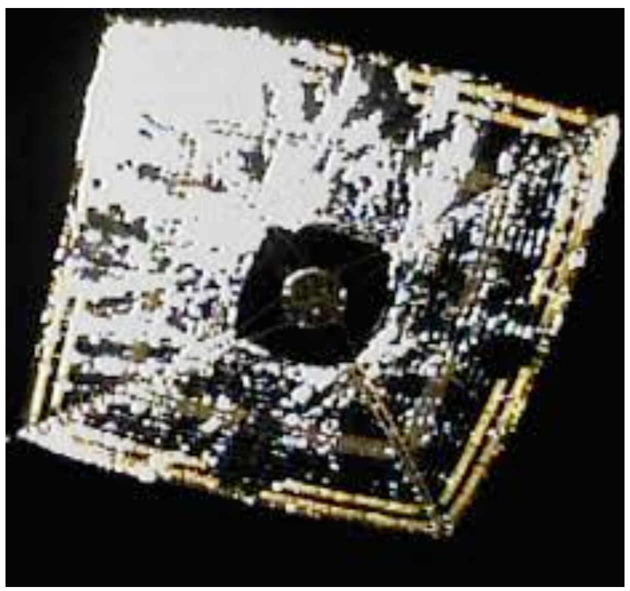
– Every photon carries momentum:

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

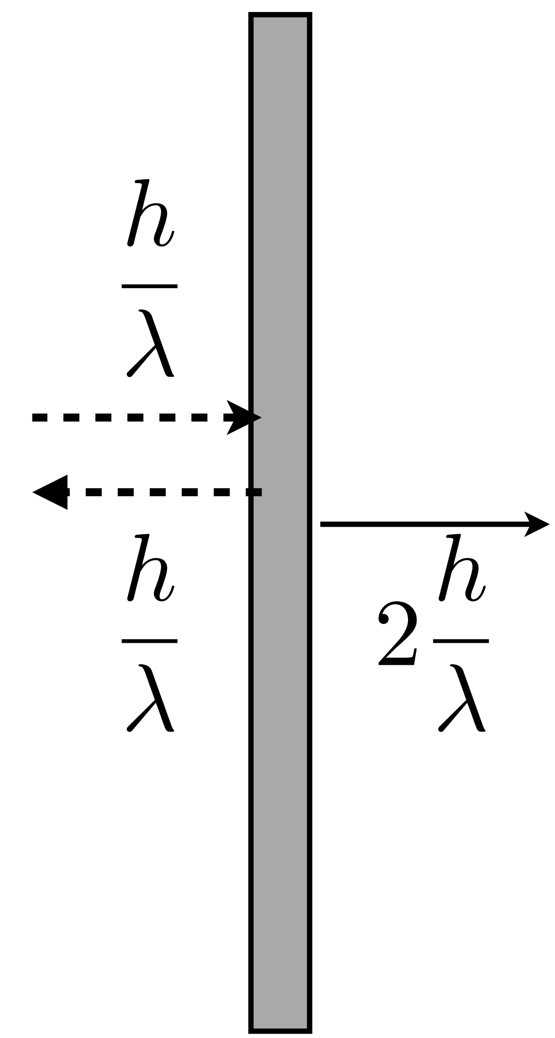
– Thus reflecting light exerts **pressure**.

– The physics behind **solar sails**.

– Each photon reflected imparts a **momentum kick** to the sail, accelerating the probe.



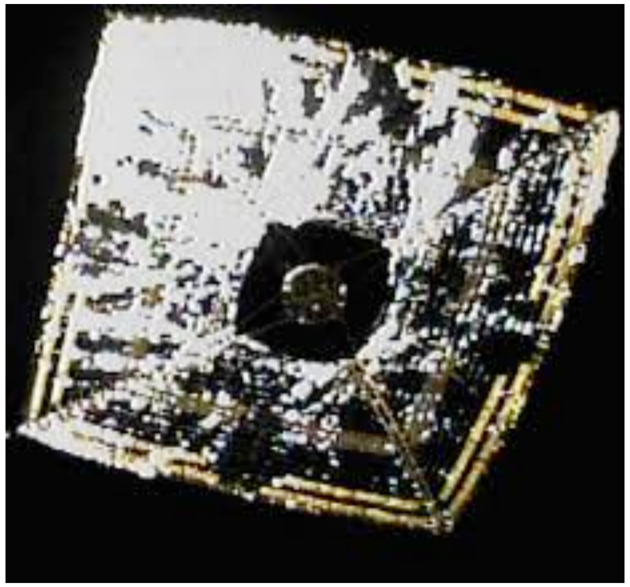
IKORAS Venus probe



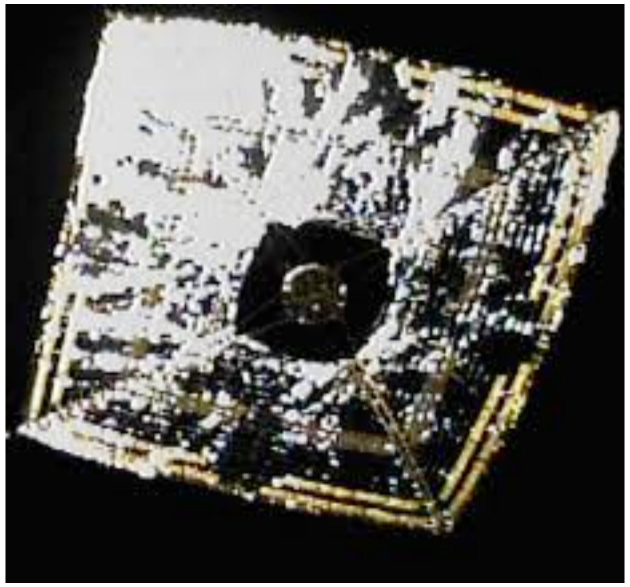
Quiz

–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**.

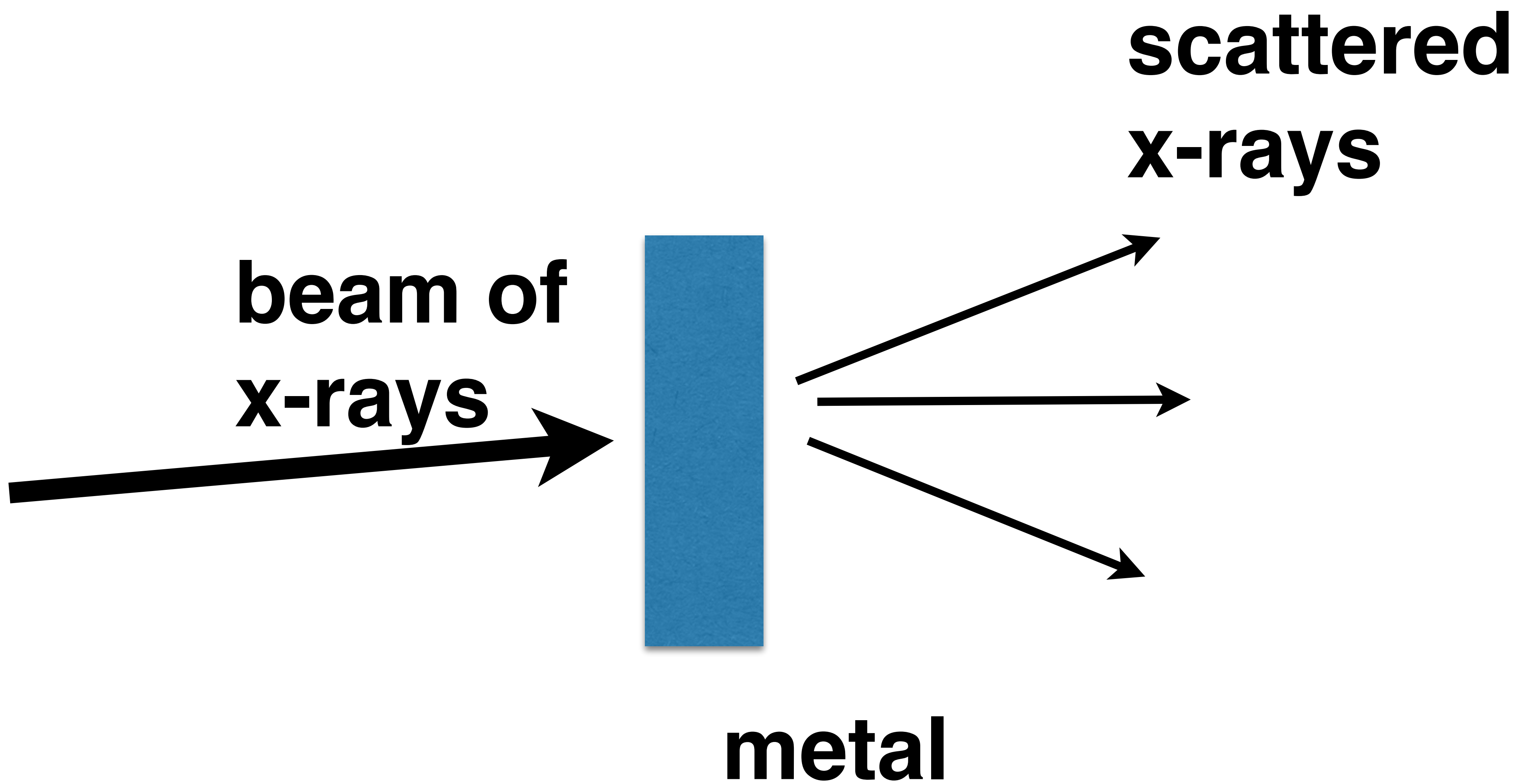
- 1922 - Compton Scattering
  - –Arthur Compton

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.**

- 1922 - Compton Scattering
  - –Arthur Compton

Arthur Compton

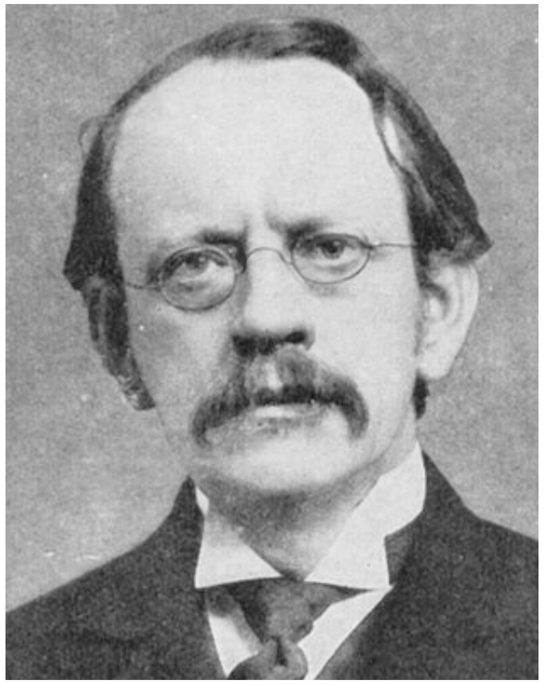


- When **X-rays** (nm light) are incident on a metal, they **scatter** from the **free electrons** in the metal.

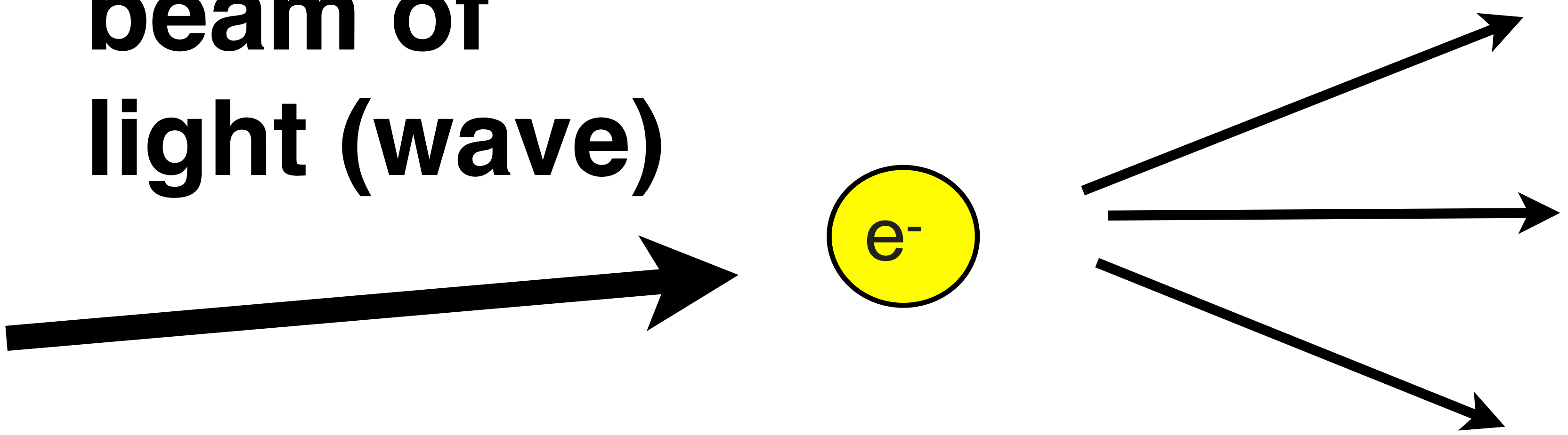
Scattered as a wave or a particle?

The Compton Effect

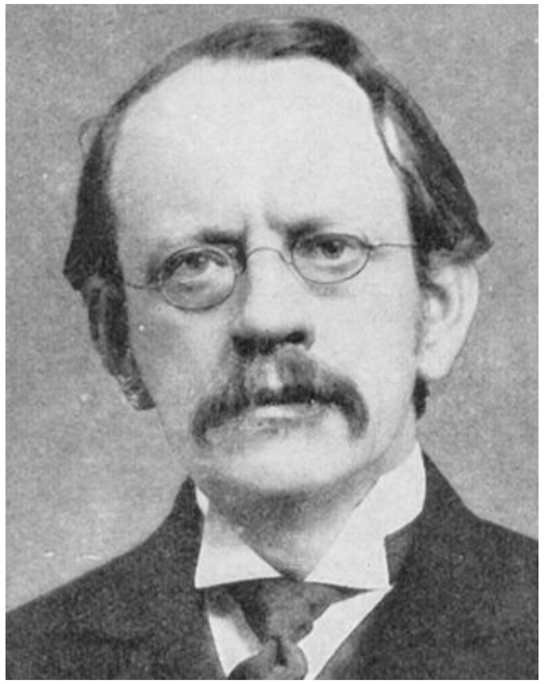
- Thomson scattering (1900s)
  - Thompson developed a theory for how **electromagnetic waves** should **scatter** from **charged particles**.



J.J. Thomson

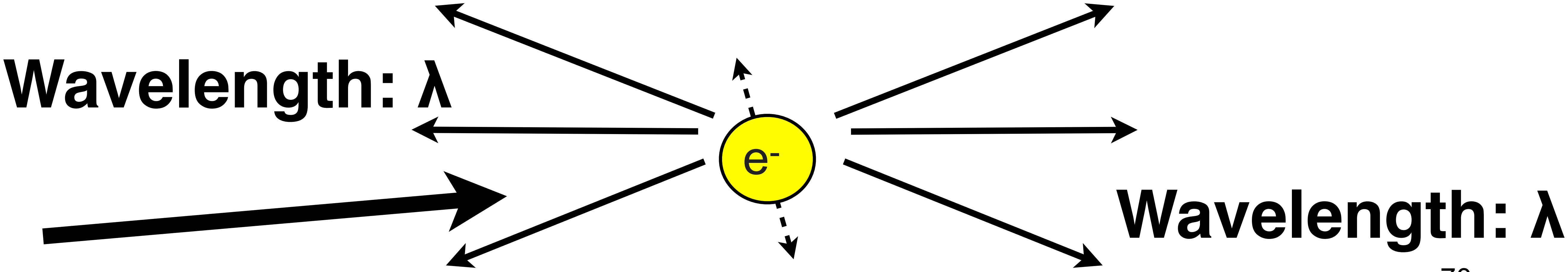


The Compton Effect



J.J. Thomson

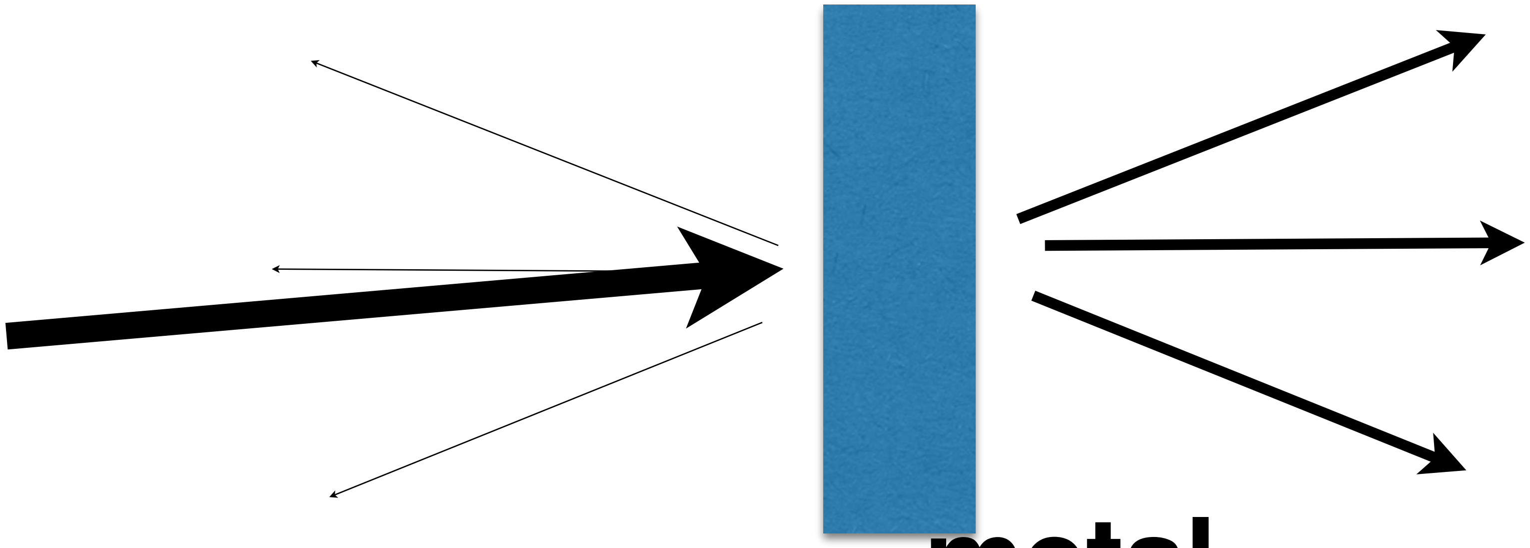
- Thomson scattering (1900s)
  - Key features:
    - The incoming wave (frequency **f=c/λ**) induces charged particle to oscillate at **same frequency** f.
    - Oscillating particle emits light at the **same frequency** f in all directions.
- An important effect in Plasma physics.



The Compton Effect

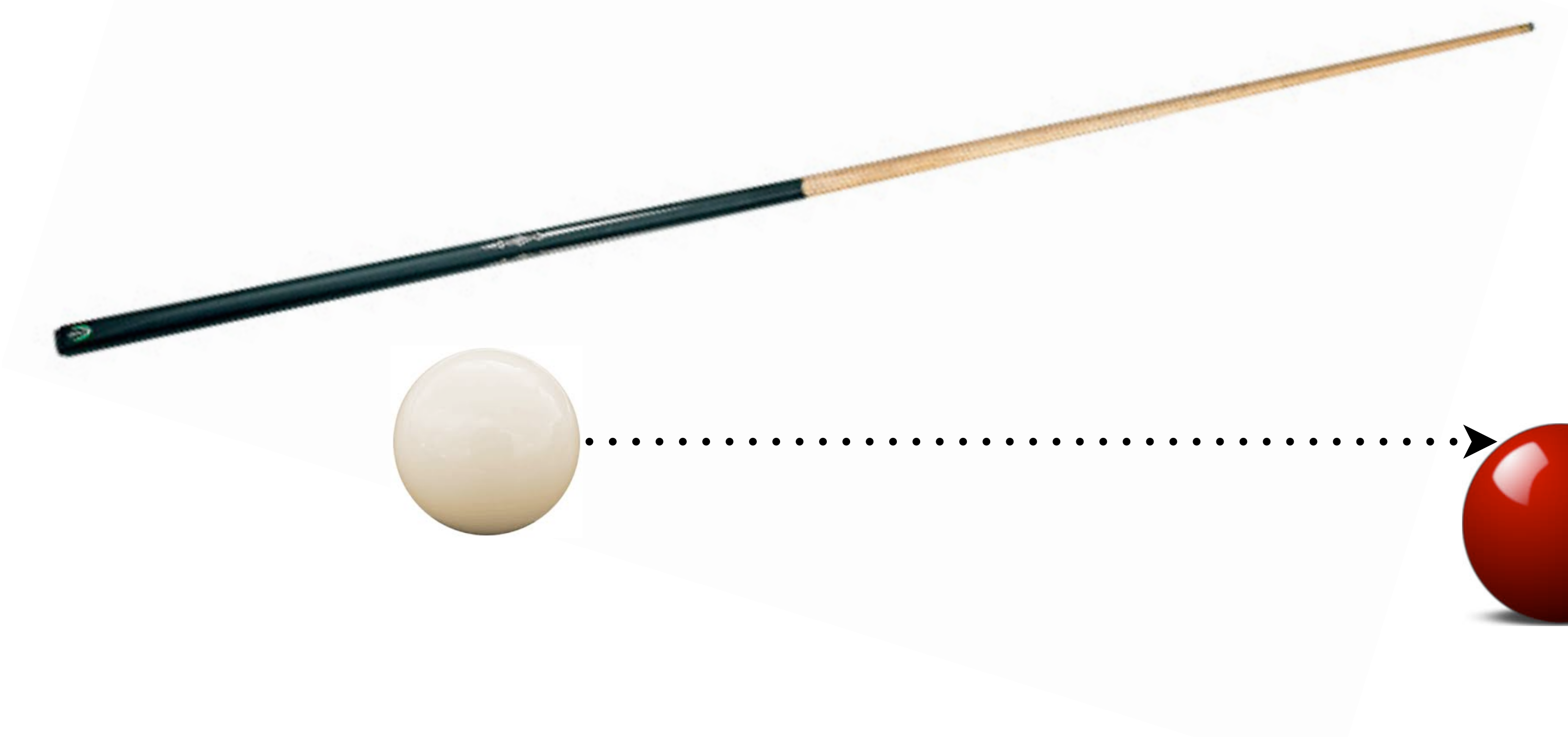
Arthur Compton

- 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

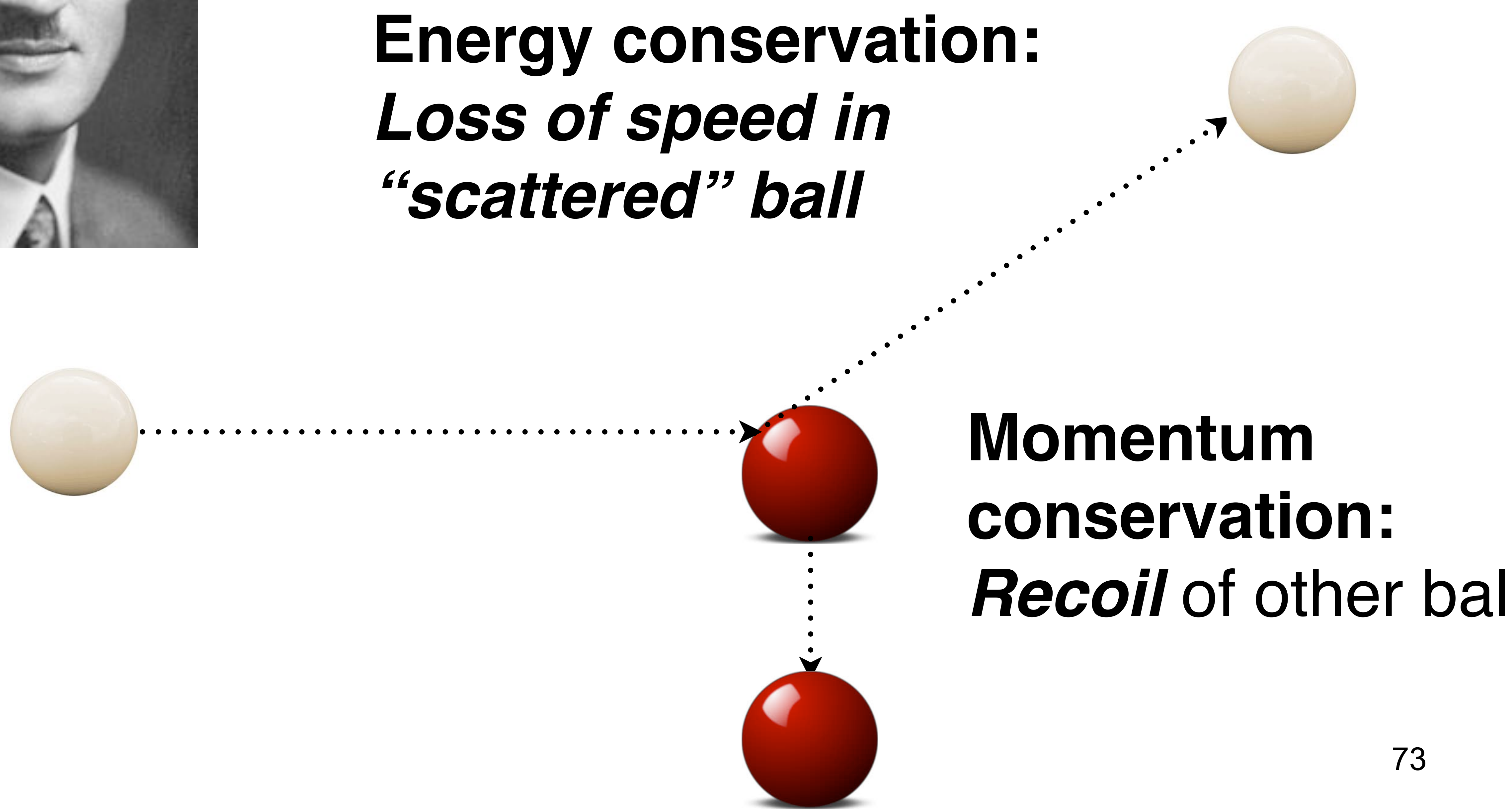
- 1922 - Compton Scattering
  - –Compton's proposal:
    - Take **Planck** and **Einstein** seriously.
  - –Treat incoming x-ray as a stream of **particles**.
  - –Model scattering as an **elastic collision**.



Scattered as a wave or a particle?

The Compton Effect

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



The Compton Effect

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

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

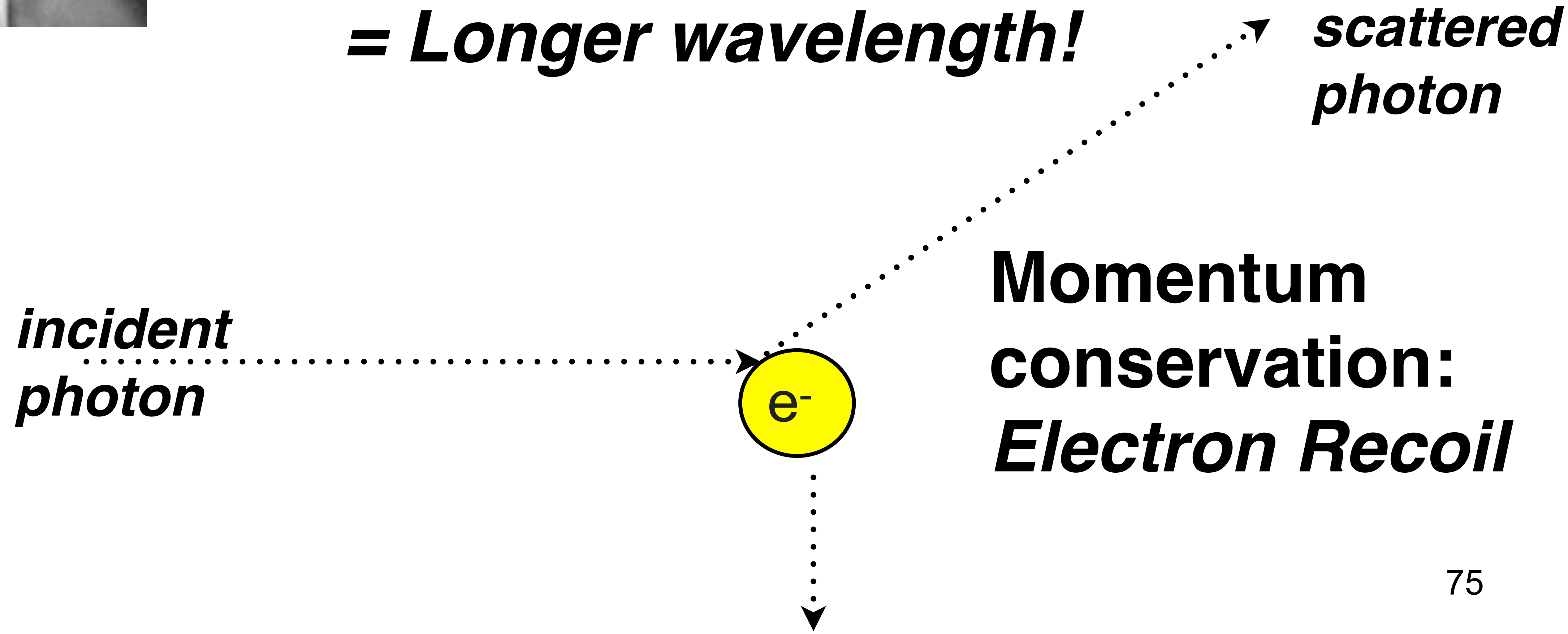
  - –Treat collision elastically
    - **Momentum** and **energy** conserved.
  - –and treat electron motion using **special relativity.**

Scattered as a wave or a particle?

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)

Energy conservation:
Loss of photon energy
= Longer wavelength!



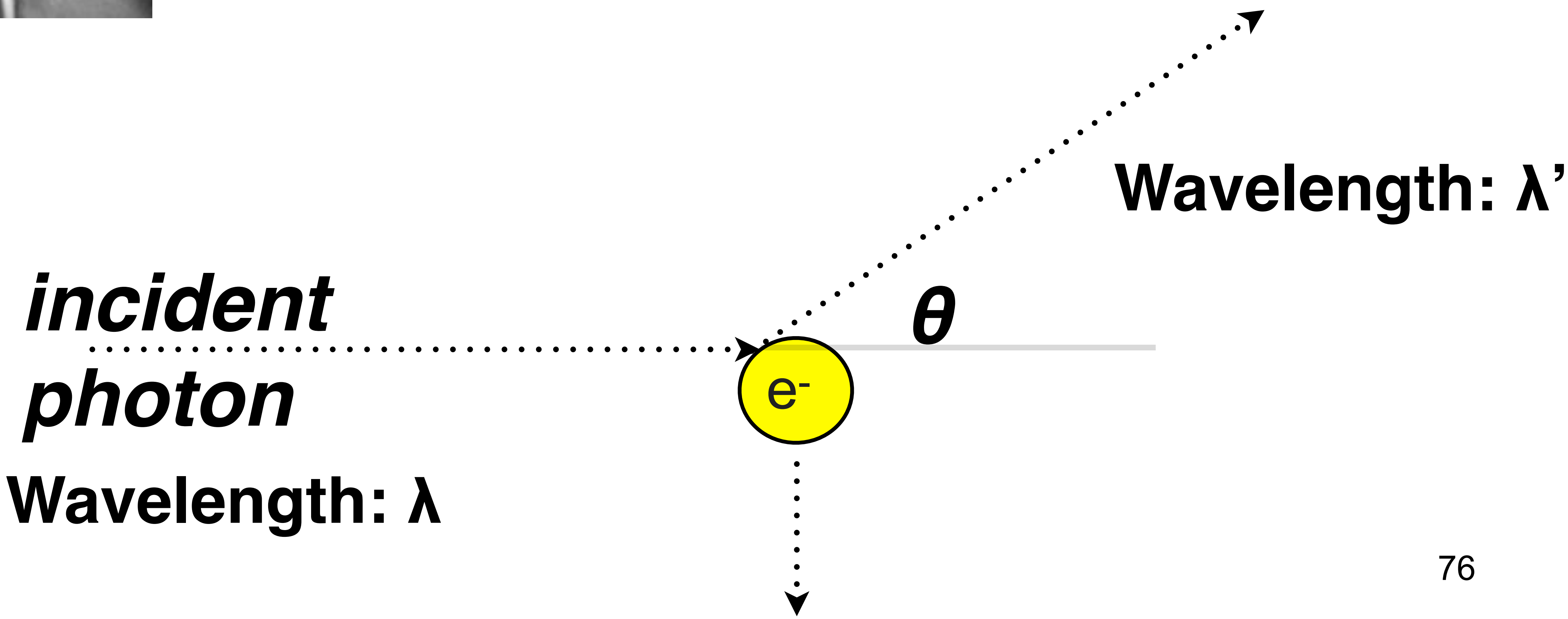
Momentum conservation:
Electron Recoil

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.



The Compton Effect

- 1922 - Compton Scattering
  - –Compton scattering formula:

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

  - –where m_e is electron mass.
- **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).

Scattered as a wave or a particle?

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:

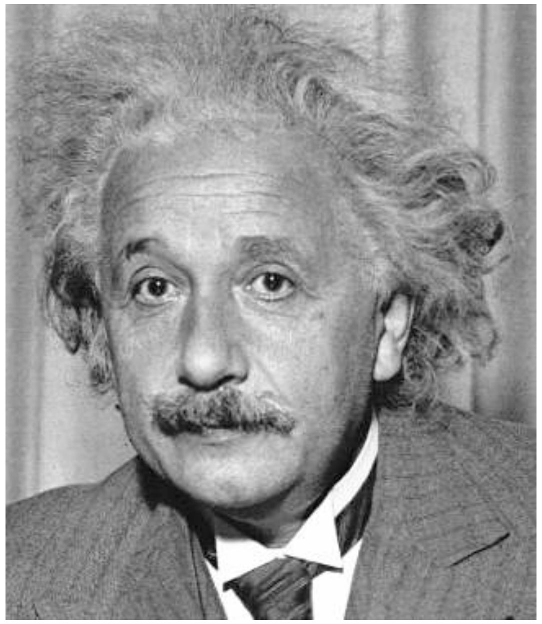
$$\lambda_\theta - \lambda_0 = 0.022 \text{ A} \quad \text{(experiment)}.$$

ding to the present theory (Eq. 5),

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

very satisfactory agreement.

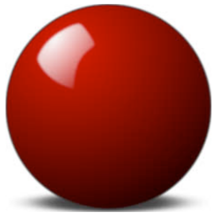
A particle and a wave?



- 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**

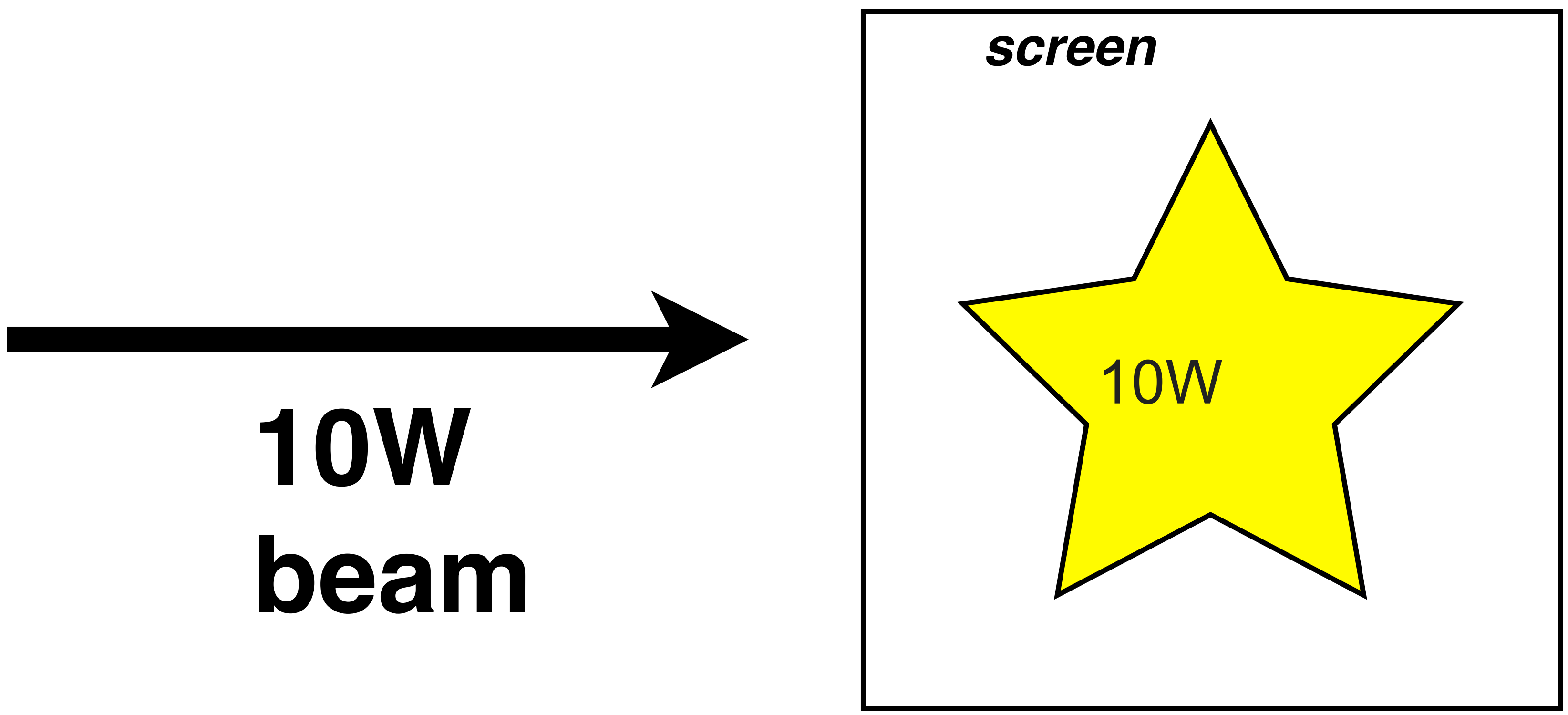
Wave-like and particle-like - the photon

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



Towards single photons

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



Towards single photons

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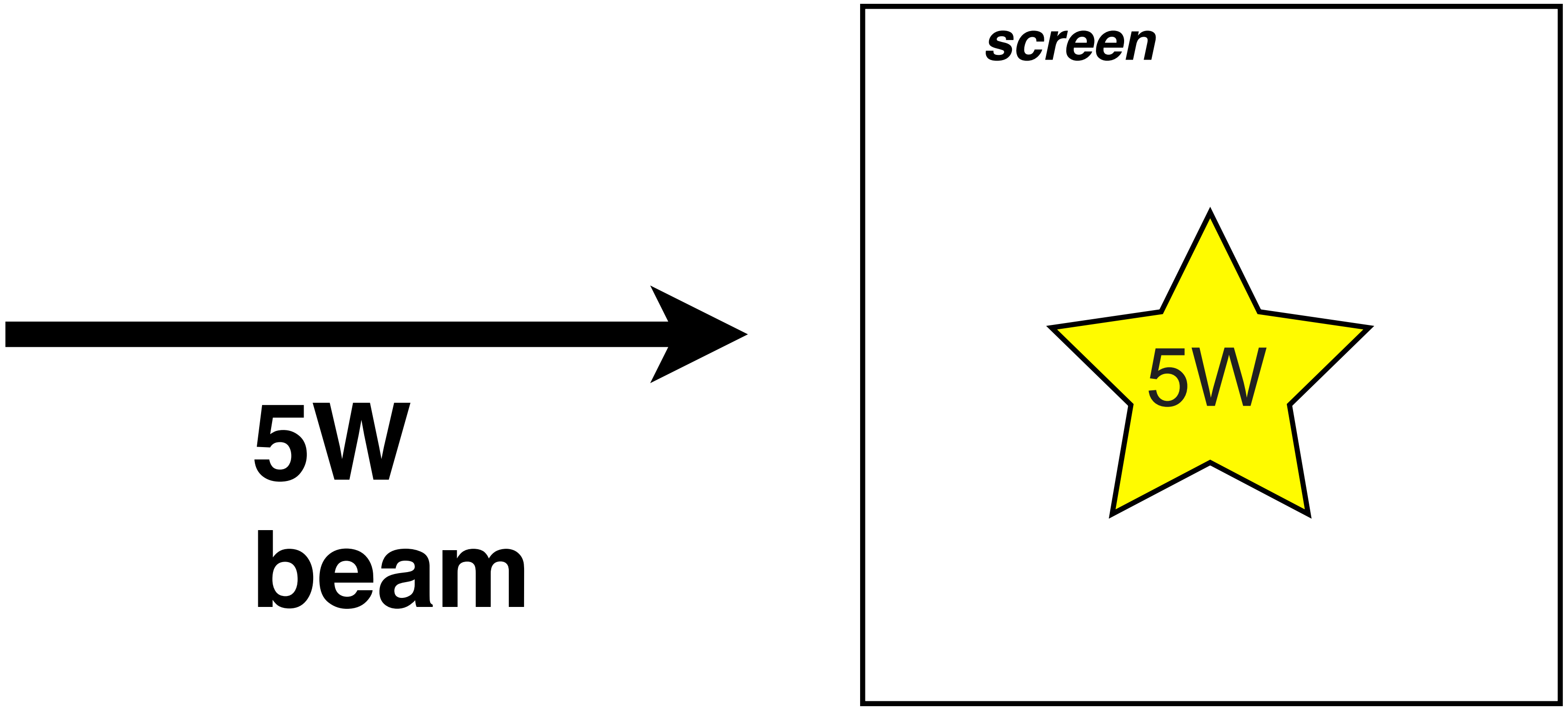

Towards single photons

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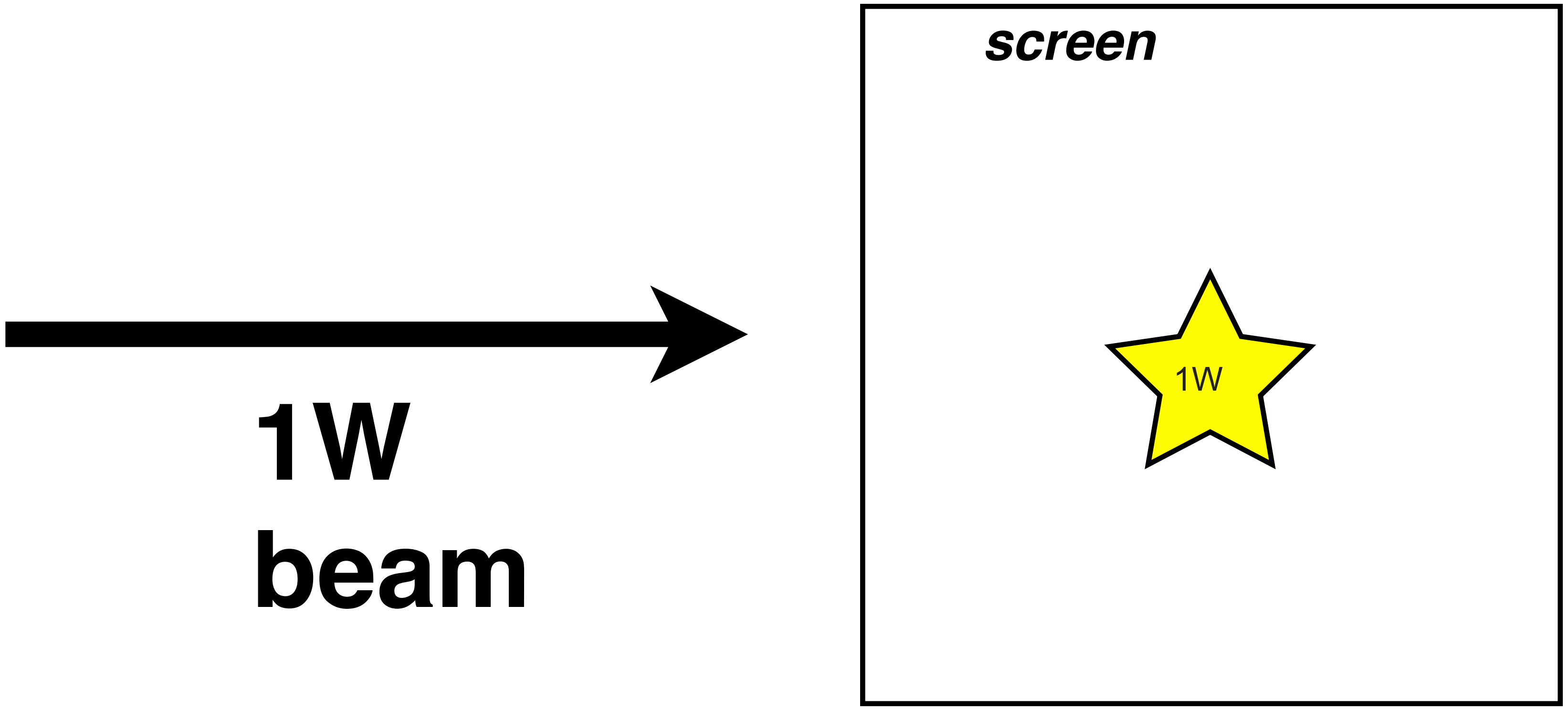

Towards single photons

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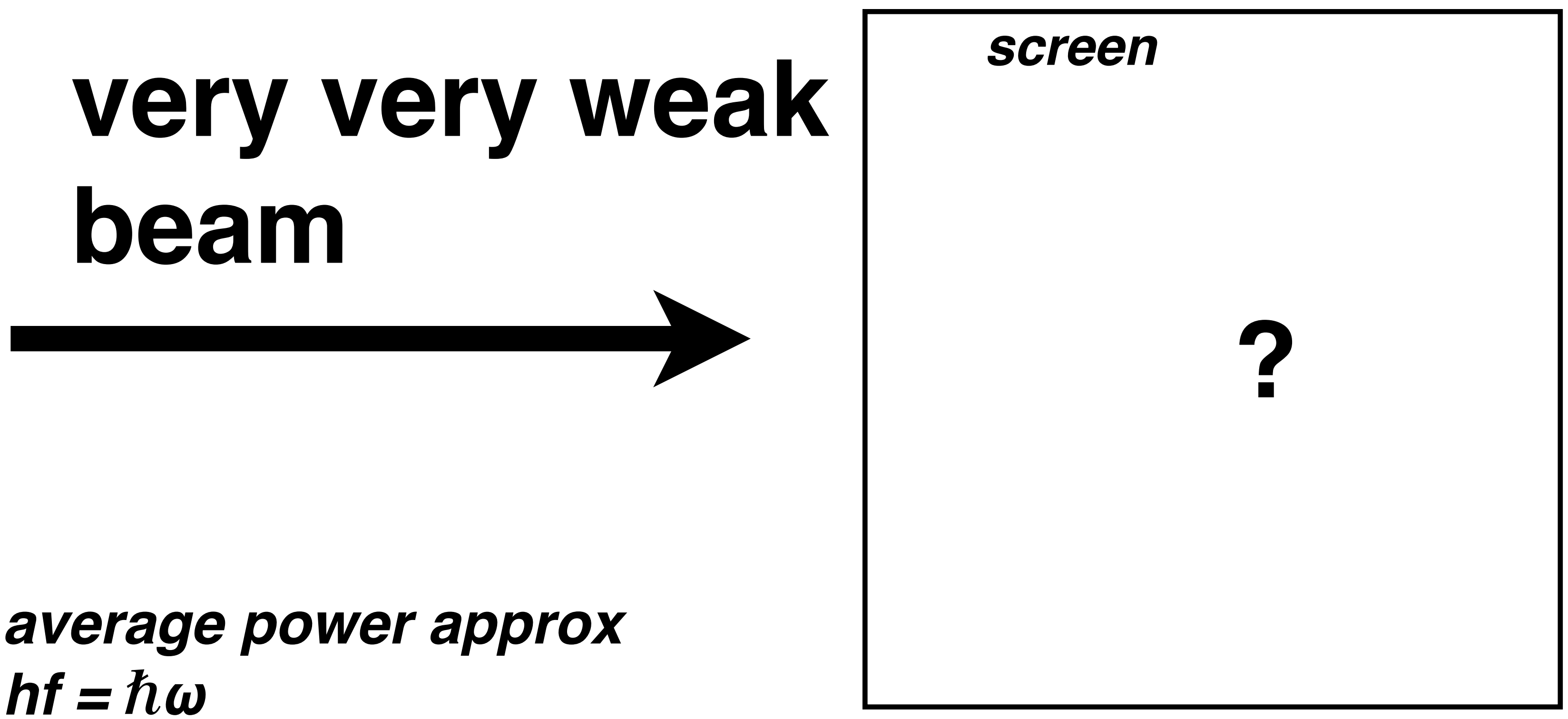


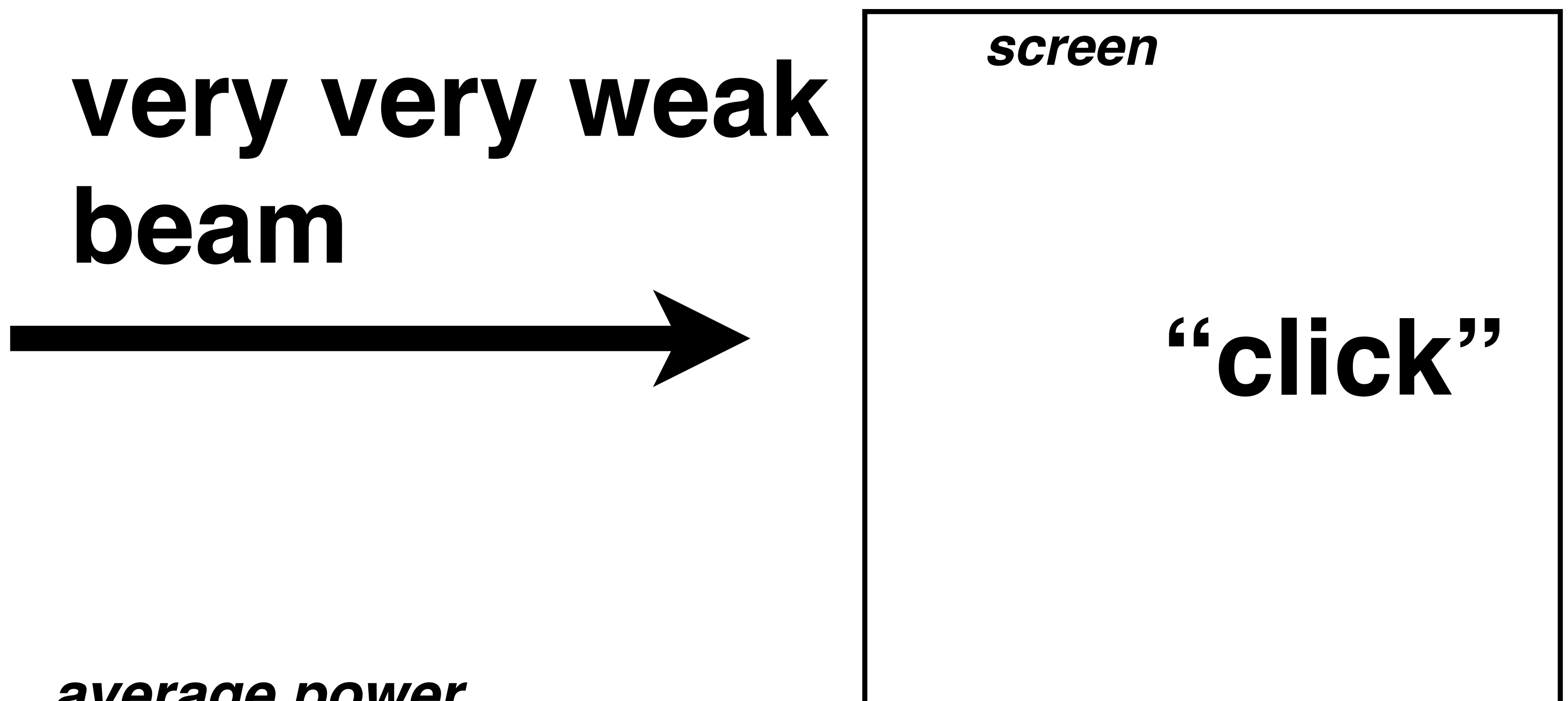
average power approx
hf = $\hbar\omega$

(one photon per second)

Freq. of a yellow photon: $f \approx 5\times10^{14}\ s^{-1}$
Energy of a yellow photon: $hf \approx 3\times10^{-19}$ J

Towards single photons

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



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Towards single photons

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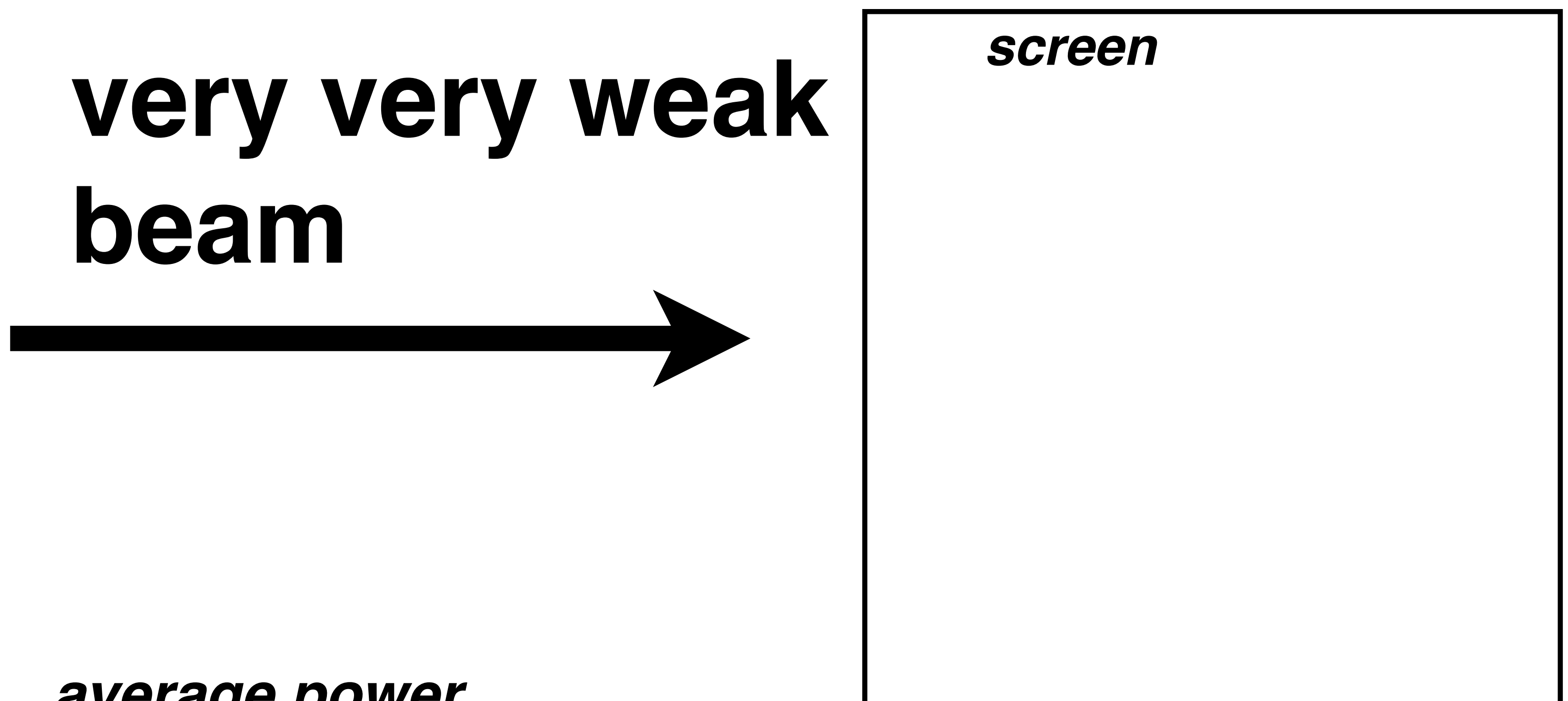
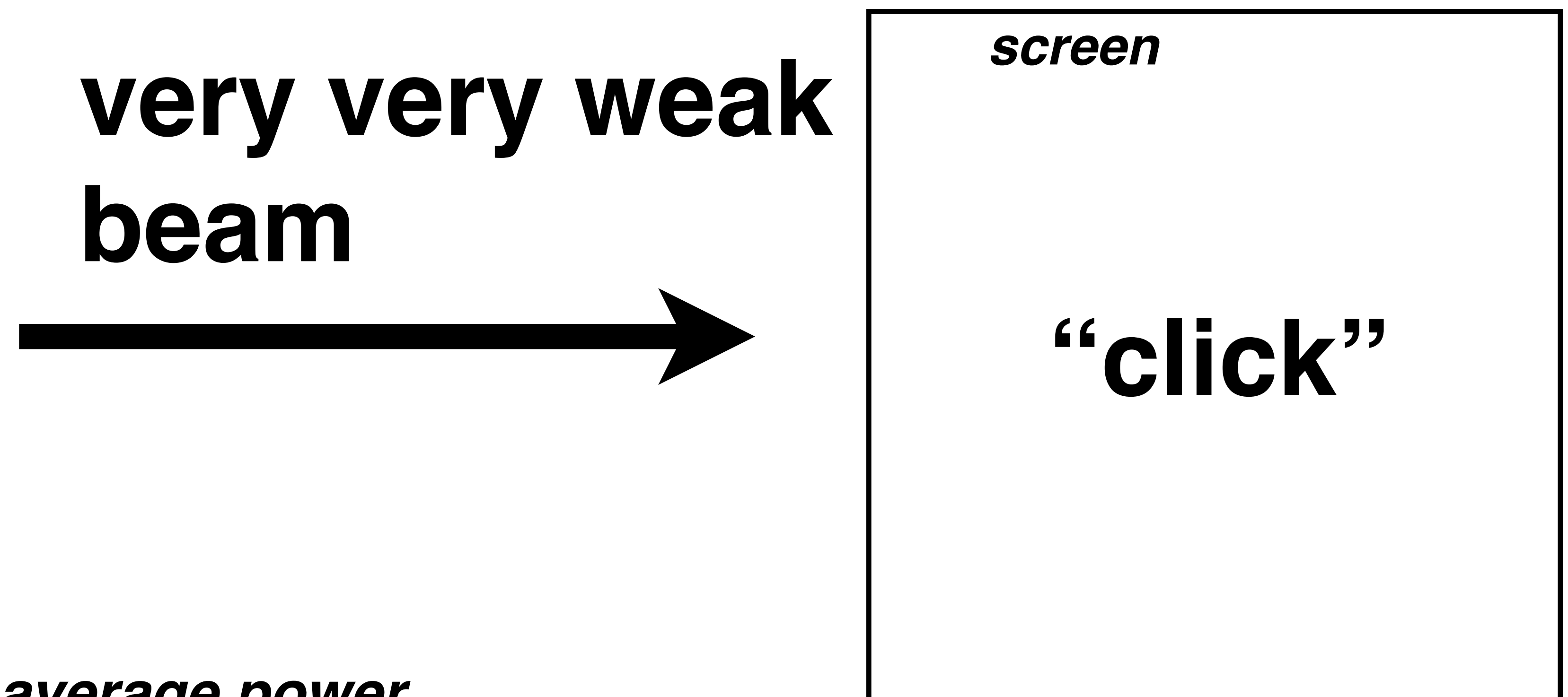


average power approx hf = $\hbar\omega$

Freq. of a yellow photon: $f \approx 5\times10^{14}\ s^{-1}$
Energy of a yellow photon: $hf \approx 3\times10^{-19}$ **J**

Towards single photons

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



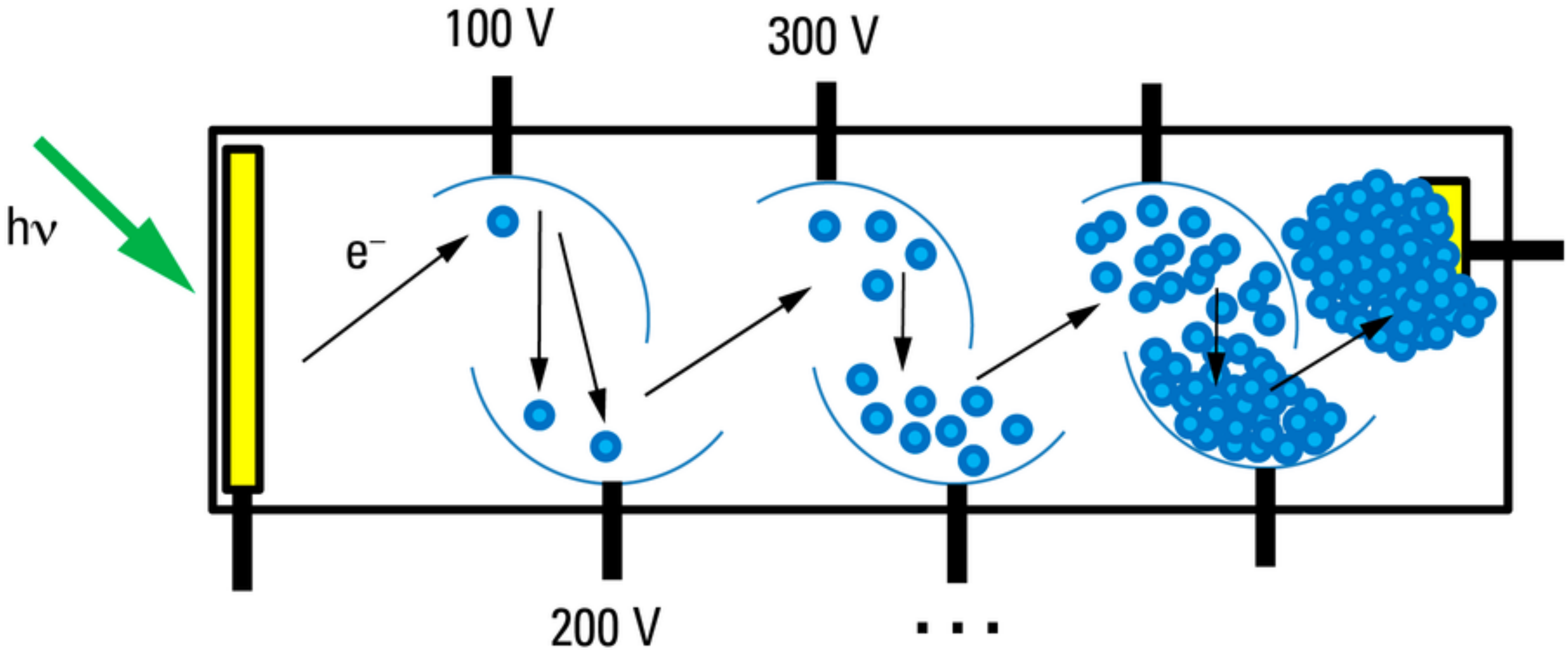
average power approx $hf = \hbar\omega$

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

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

Aside: Photomultiplier Tube

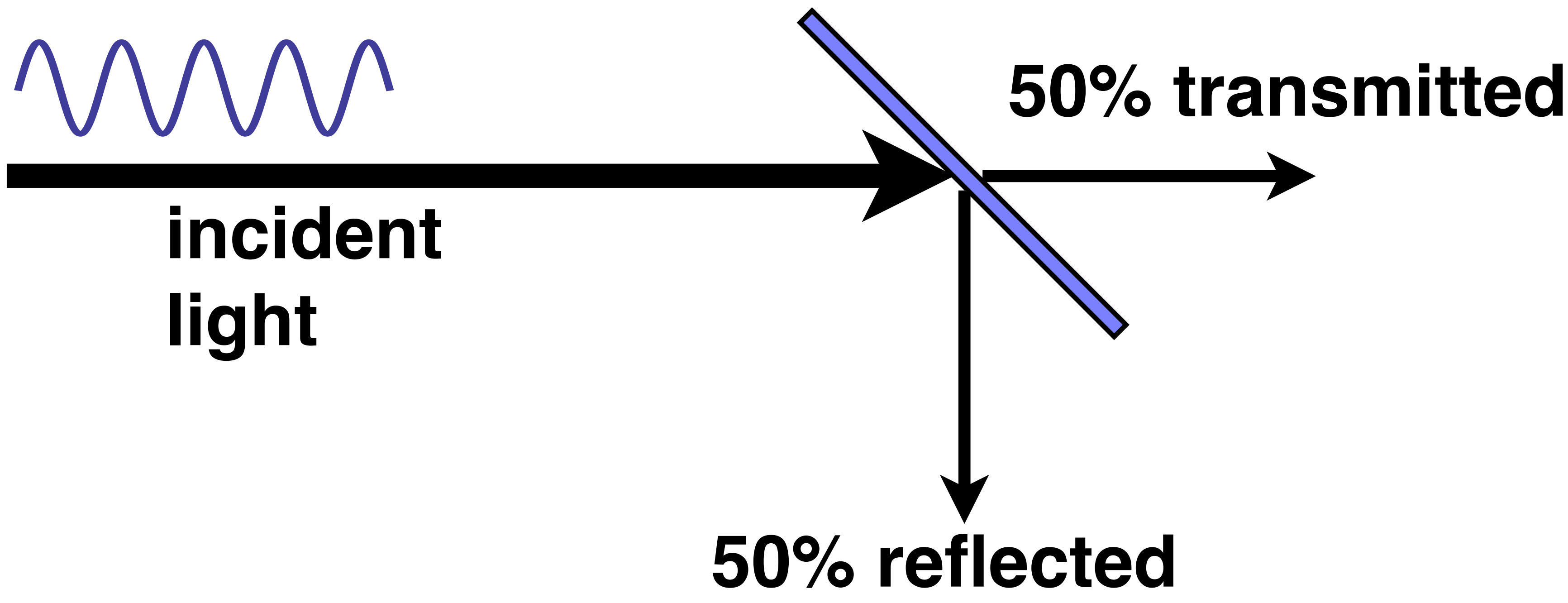
- How do you detect a single photon?



http://www.leica-microsystems.com/science-lab/from-light-to-mind-sensors-and-measuring-techniques-in-confocal-microscopy/

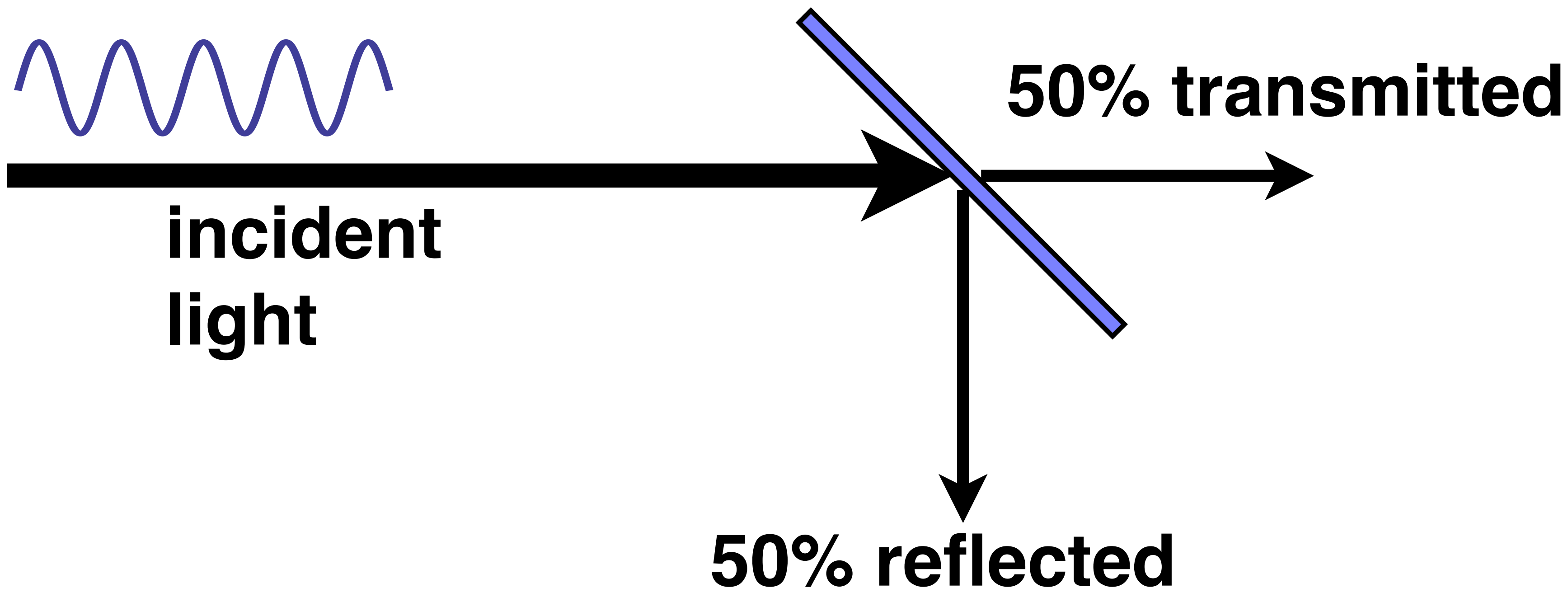
Photons on a beam splitter

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



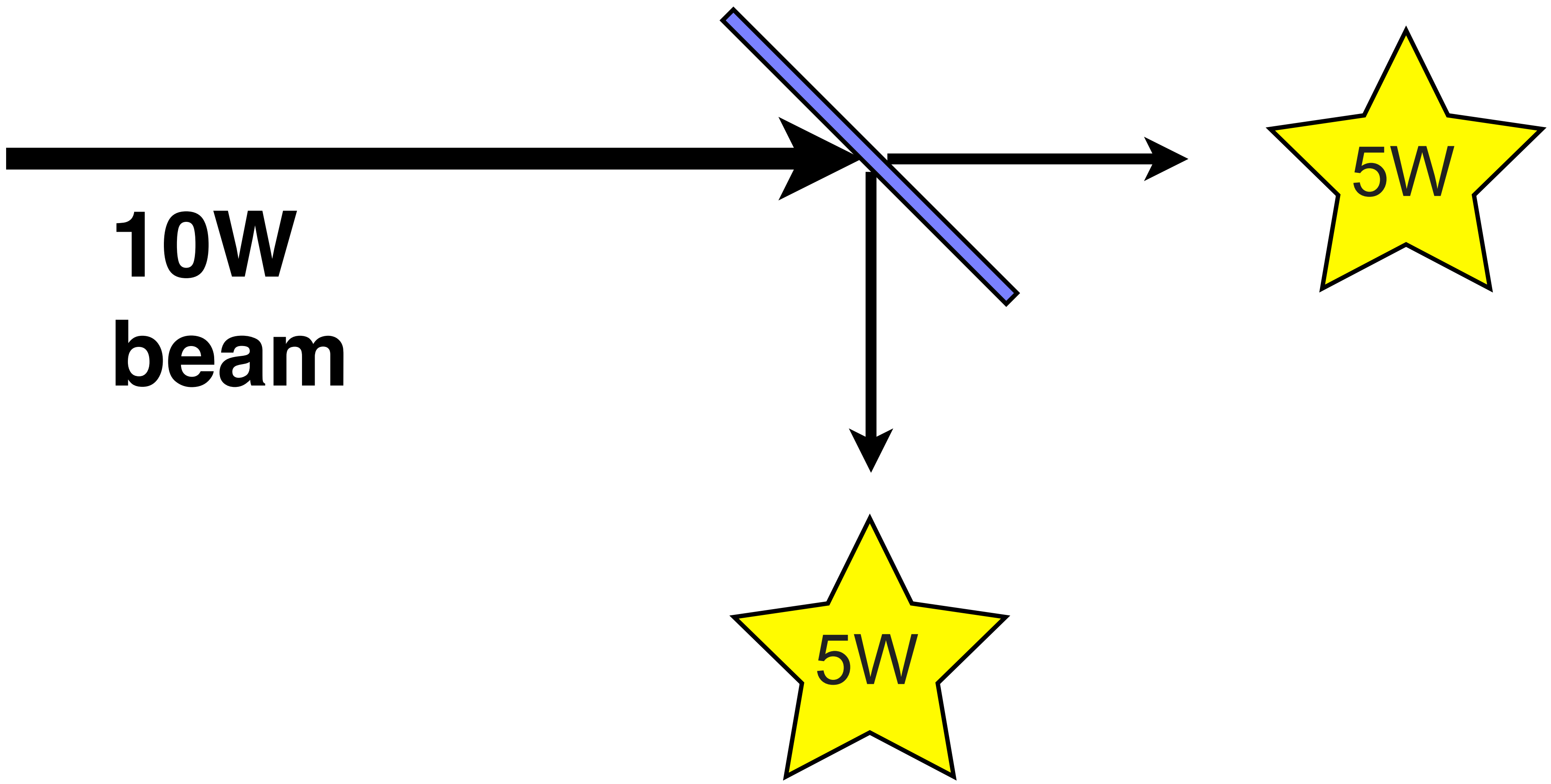
Photons on a beam splitter

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



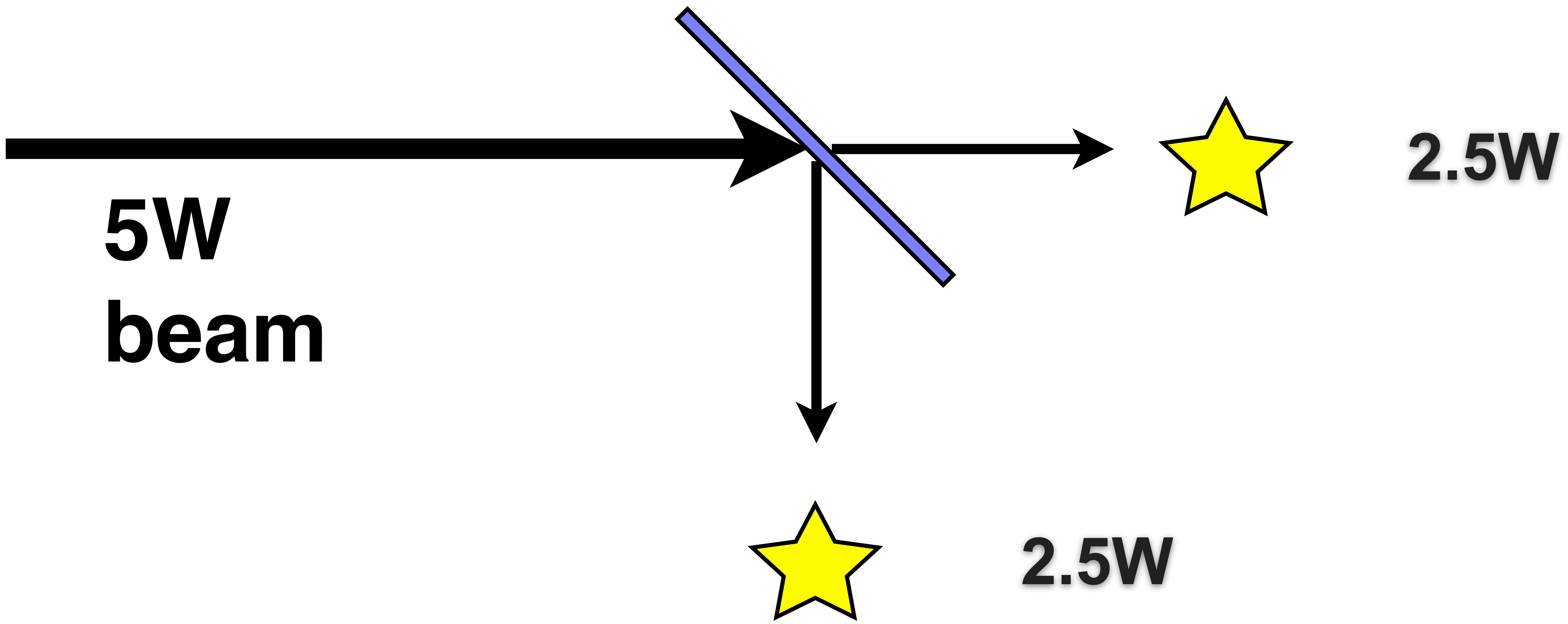
Photons on a beam splitter

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



Photons on a beam splitter

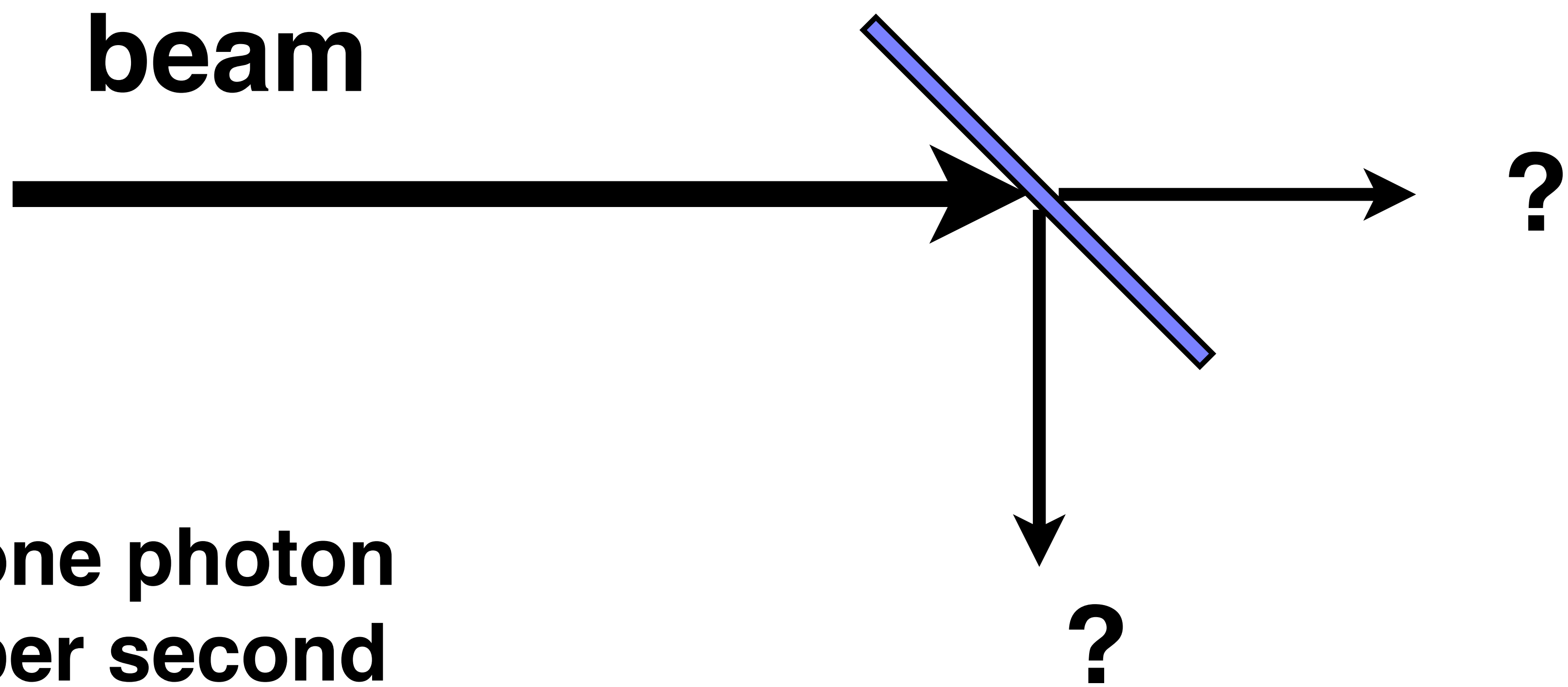
- Recall the beam splitter
  - *50% light transmitted*
  - *50% light reflected*



Photons on a beam splitter

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

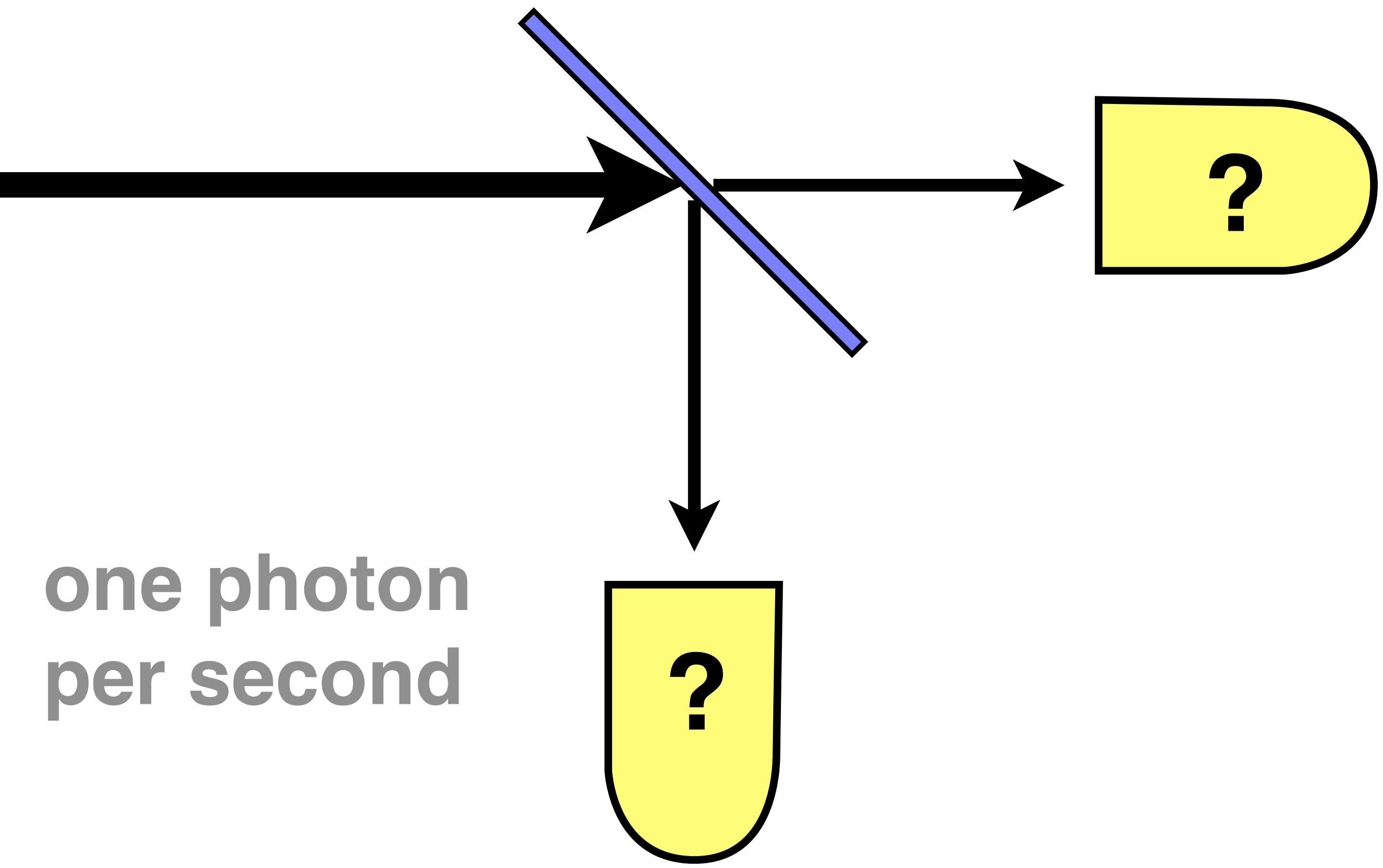
very very weak beam



one photon per second

Quiz

very very weak beam

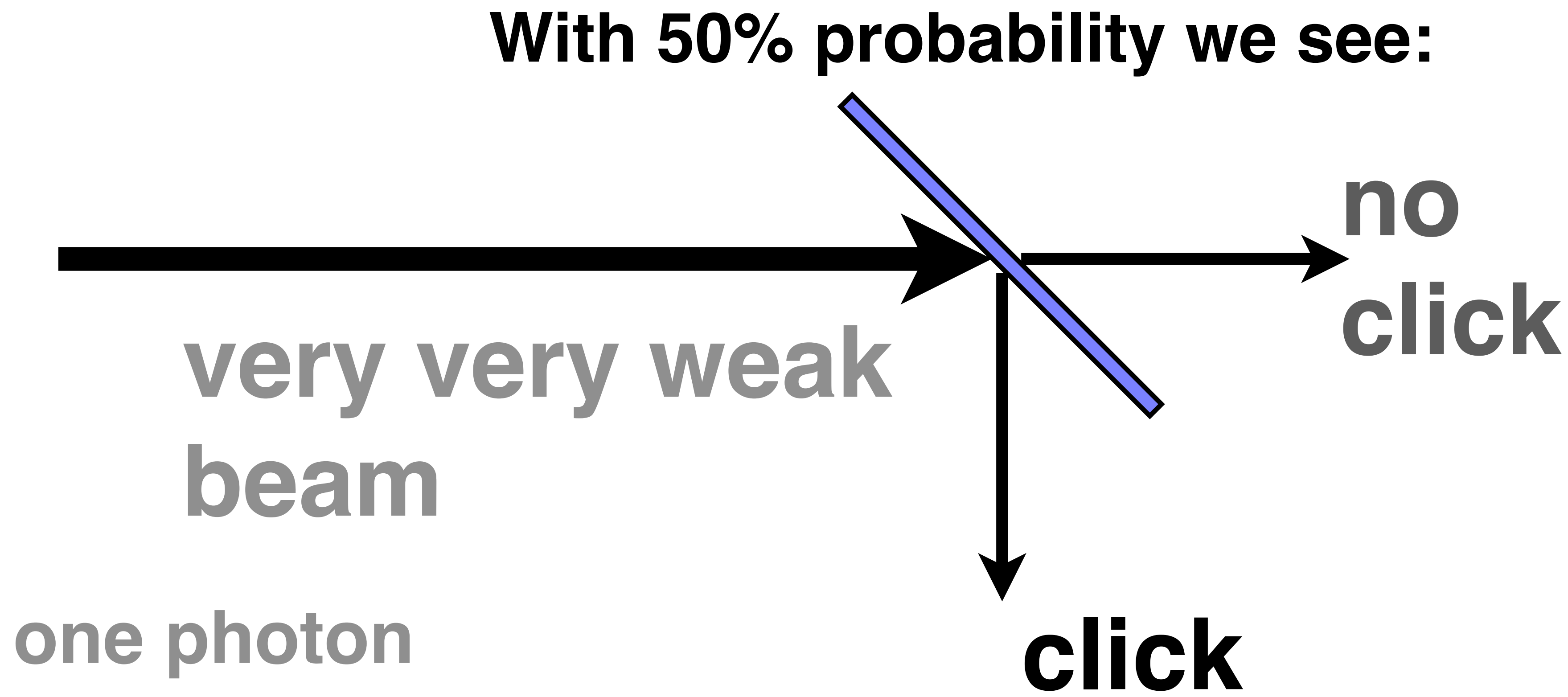


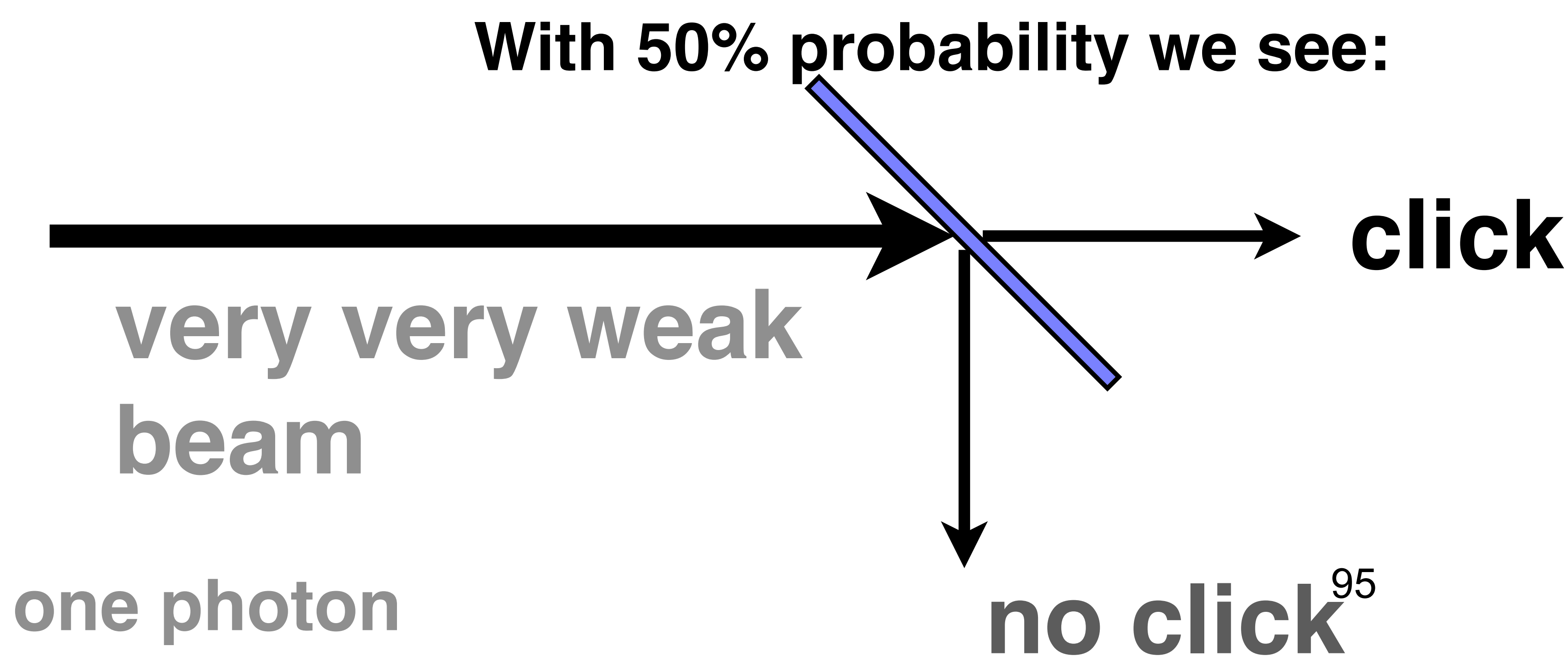
one photon per second

- ***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.

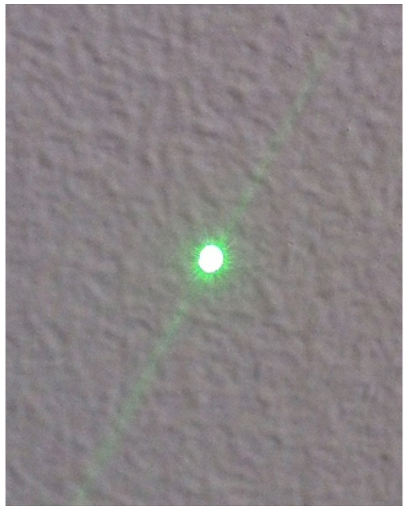




Classical limit and Quantum limit

1 photon **"click"**

10^{15} photons / sec



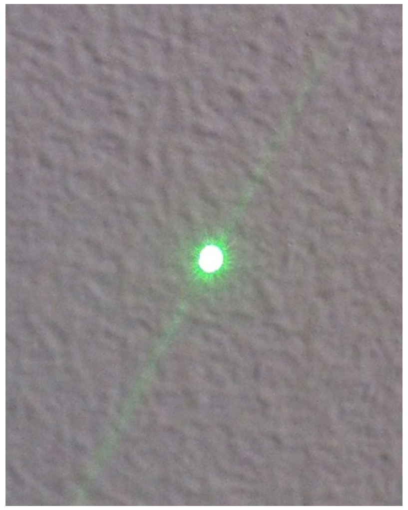
- Quantum Limit
  - –Small numbers of photons
  - –Quantum behaviour dominates
  - –Quantum mechanics **essential**
- Classical Limit
  - –Very large numbers of photons
  - –Quantum behaviour "averages away"
  - –Classical physics a **very good approximation**.

Classical limit and Quantum limit

1 photon

"click"

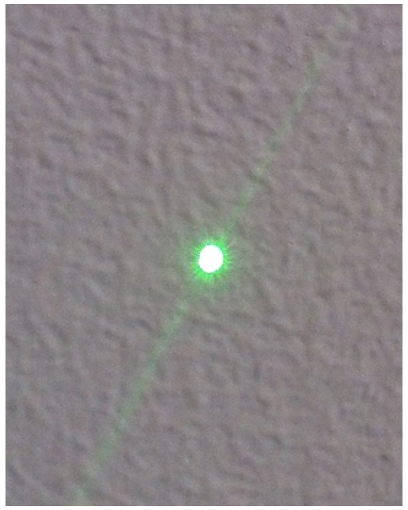
10^{15} photons / sec



- **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"**

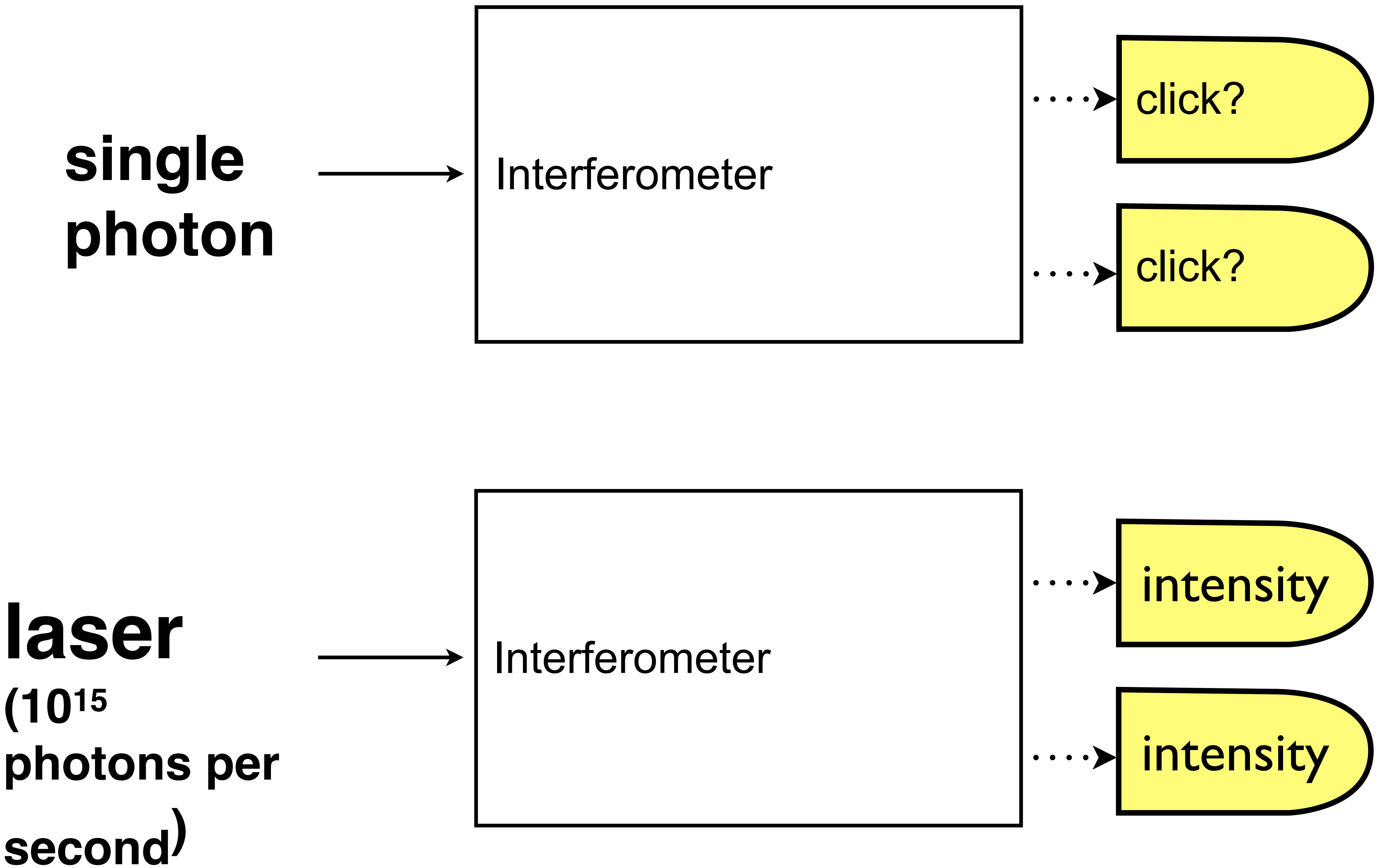


10^{15} photons / sec

- 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.

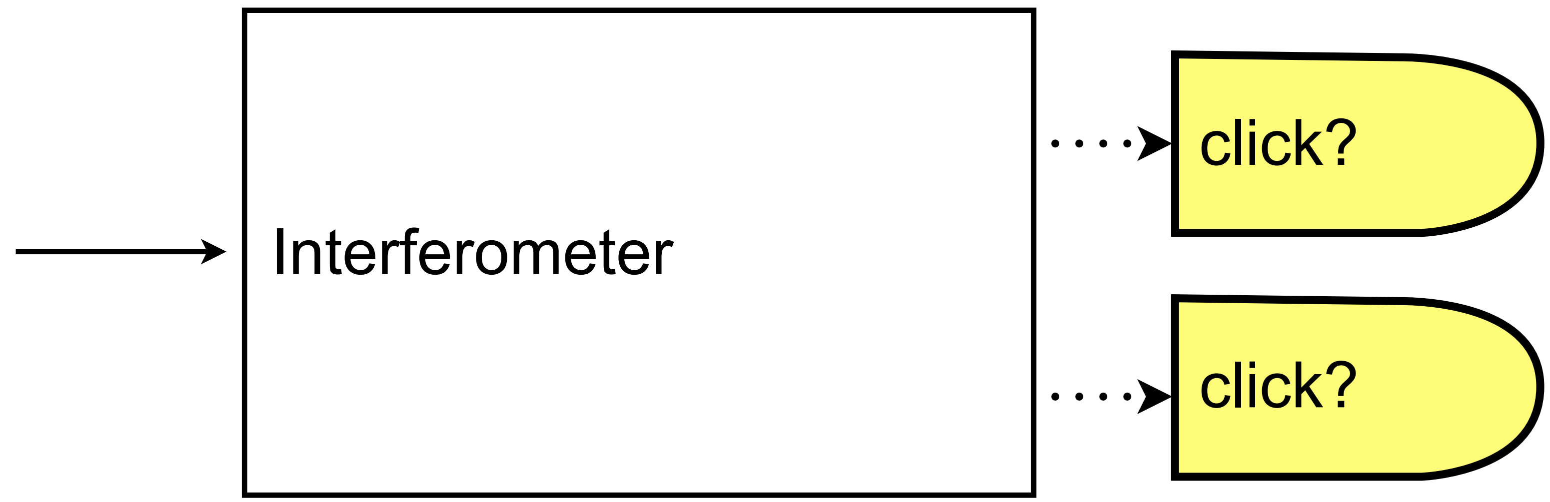


Single photon vs laser

- Consider two almost identical interference experiments.

Quantum Limit

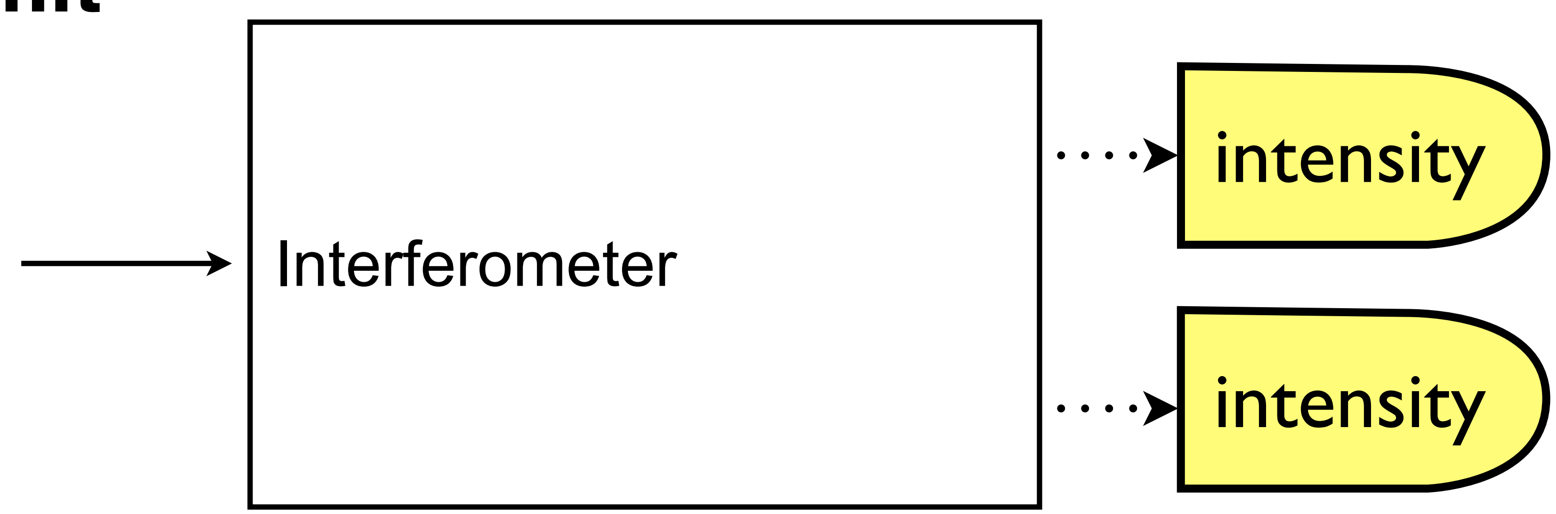
single photon



Classical Limit

laser

(10^{15} photons per second)

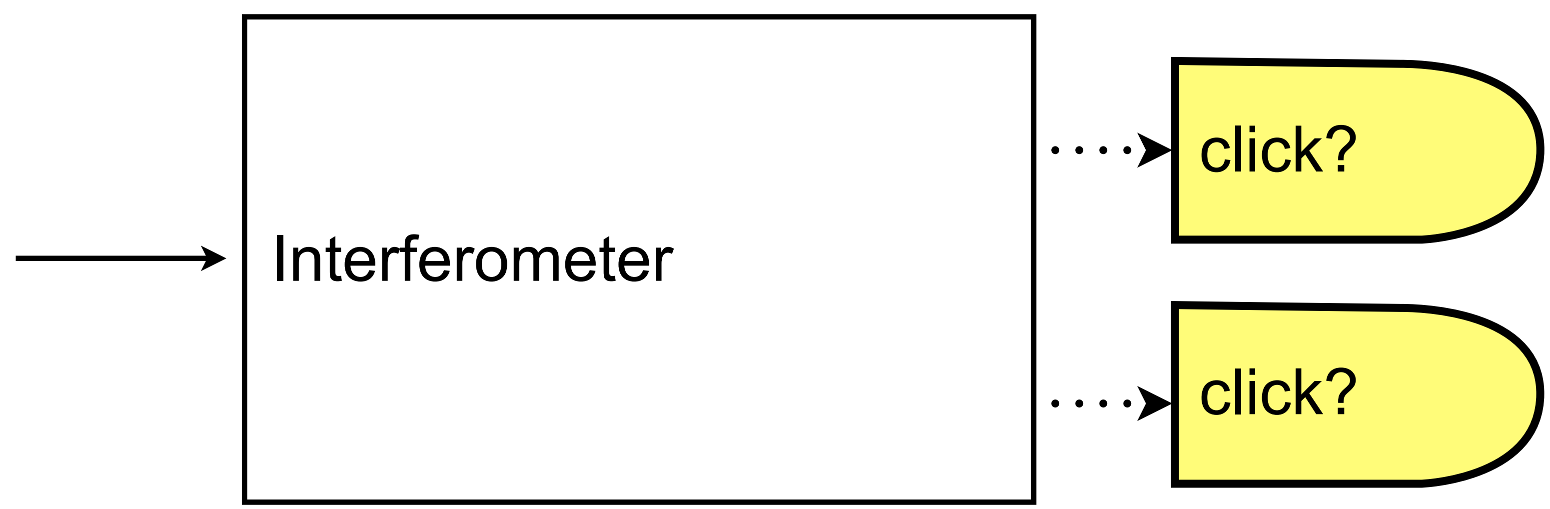


Single photon vs laser

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

Quantum Limit

single photon



Classical Limit

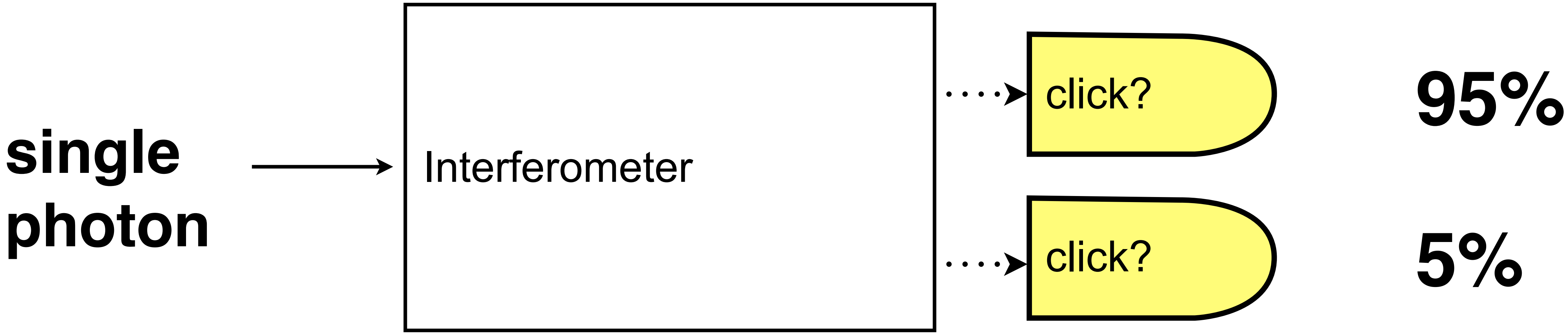
laser

(10^{15} photons per second)

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

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

Quantum Limit

single photon

95%

5%

– What will be the intensities observed in the same experiment with a 10W laser?

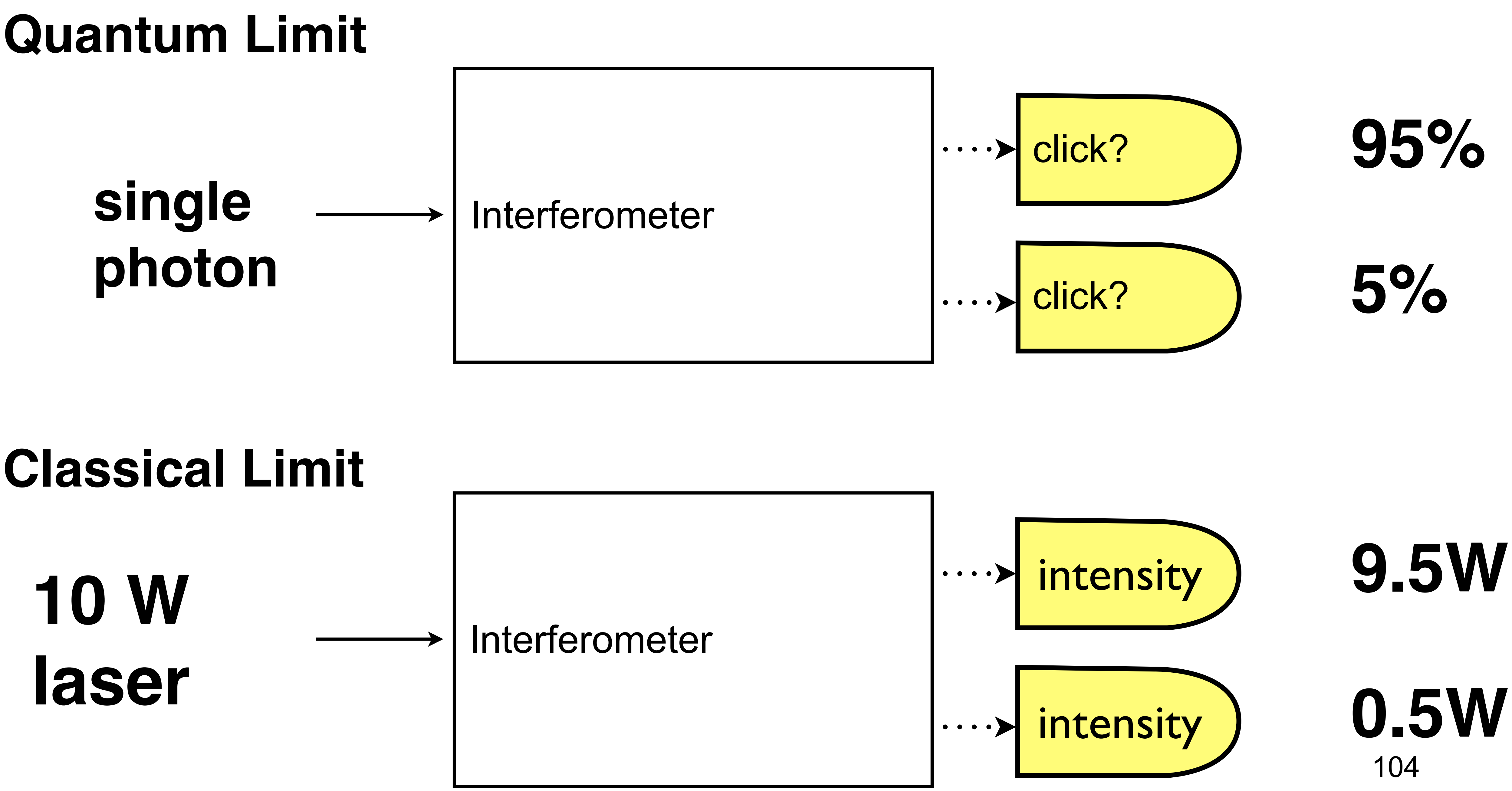
» 1. Top: 5 W Bottom: 5 W

» **2. Top: 9.5 W, Bottom: 0.5W**

» 3. Something else

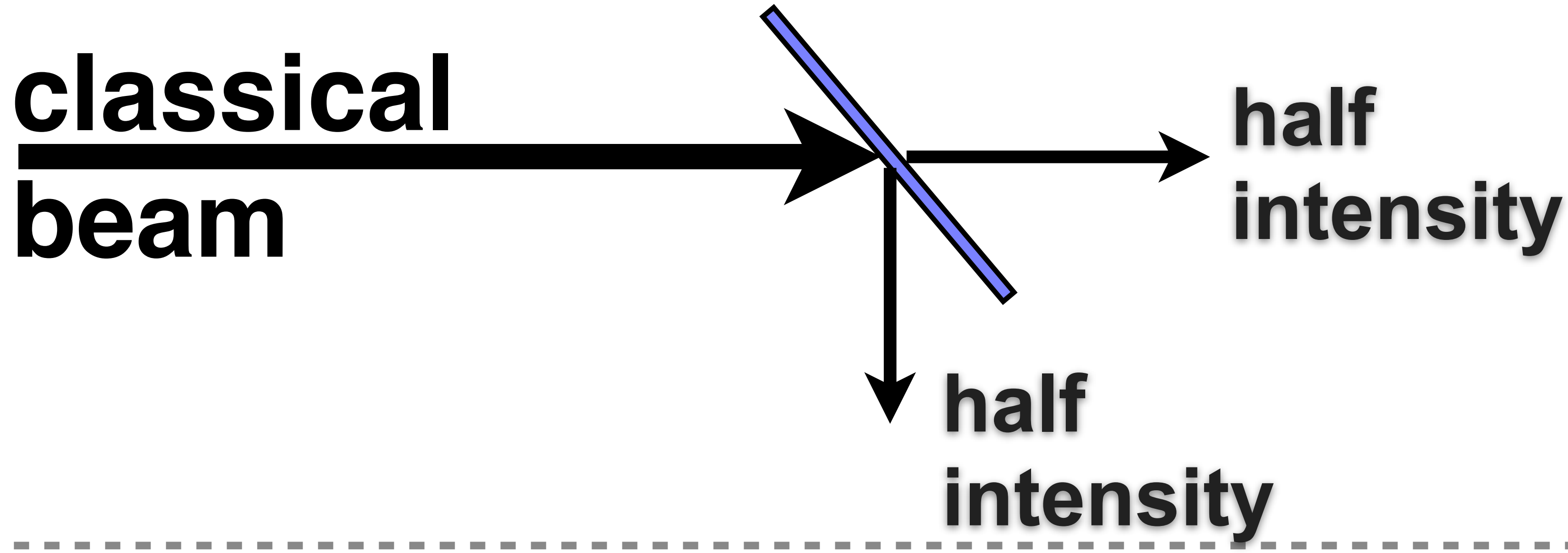
Single photon probability rule

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

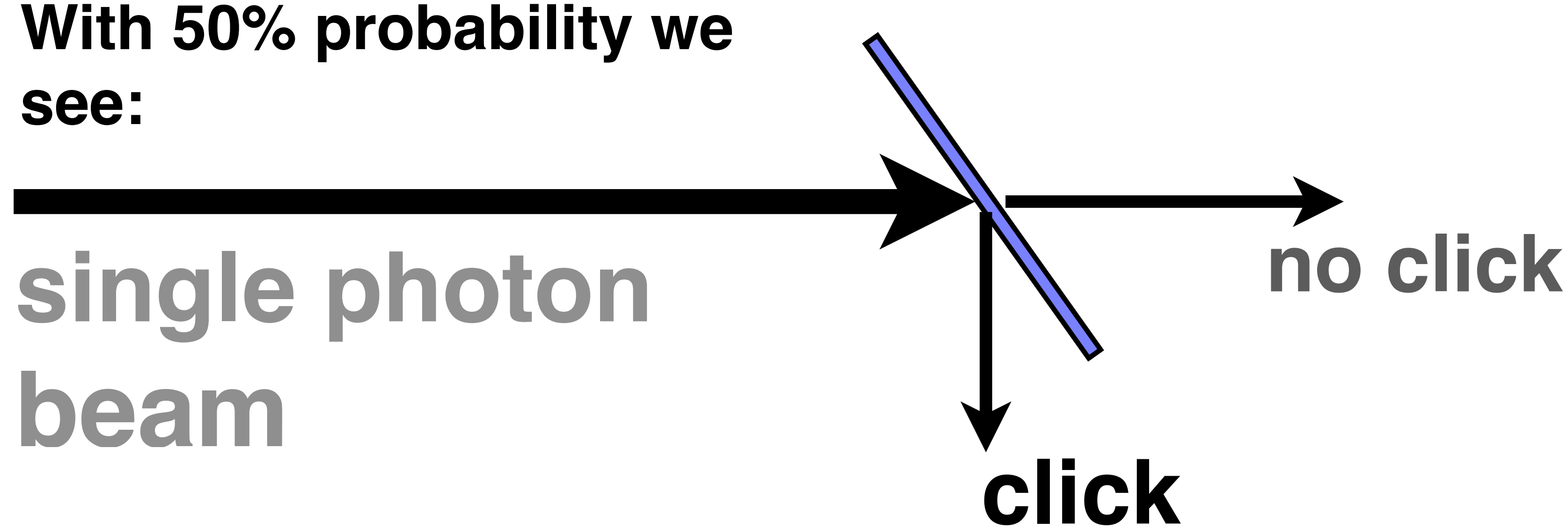


Probability rule examples

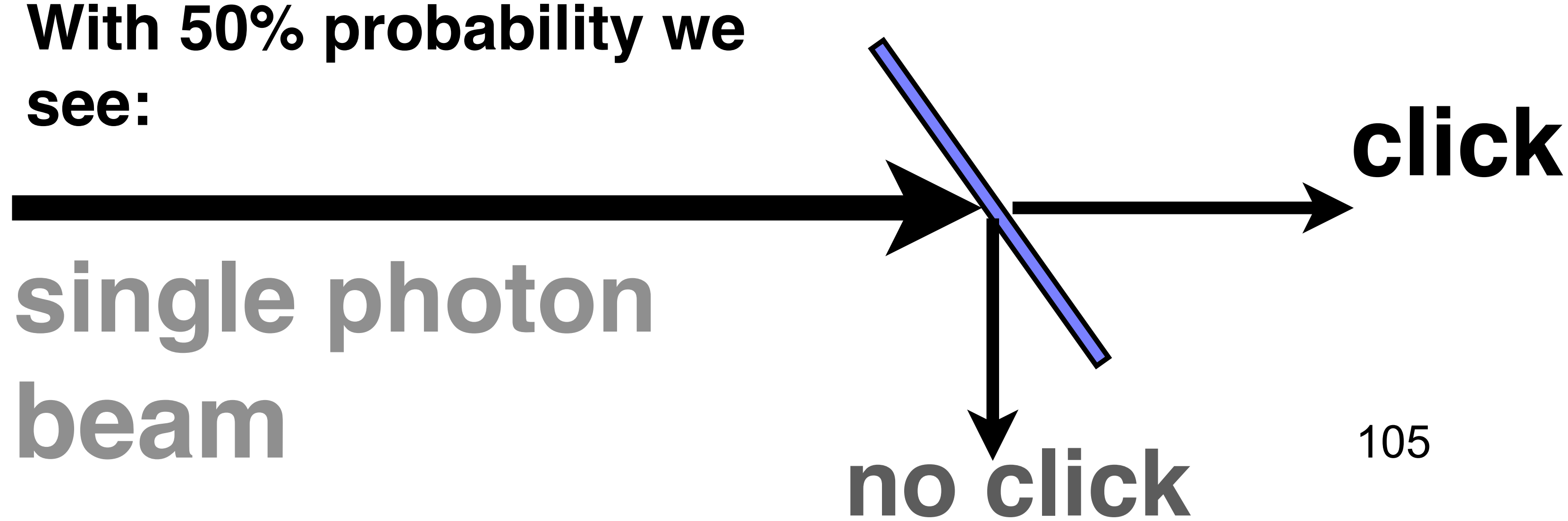
- Using this probability rule, we can look again at a single photon on a beam splitter.
- Classical intensity is split **50:50**.
- Photon can only click in 1 detector.
- Hence there must be a 50% probability for a click in each detector.



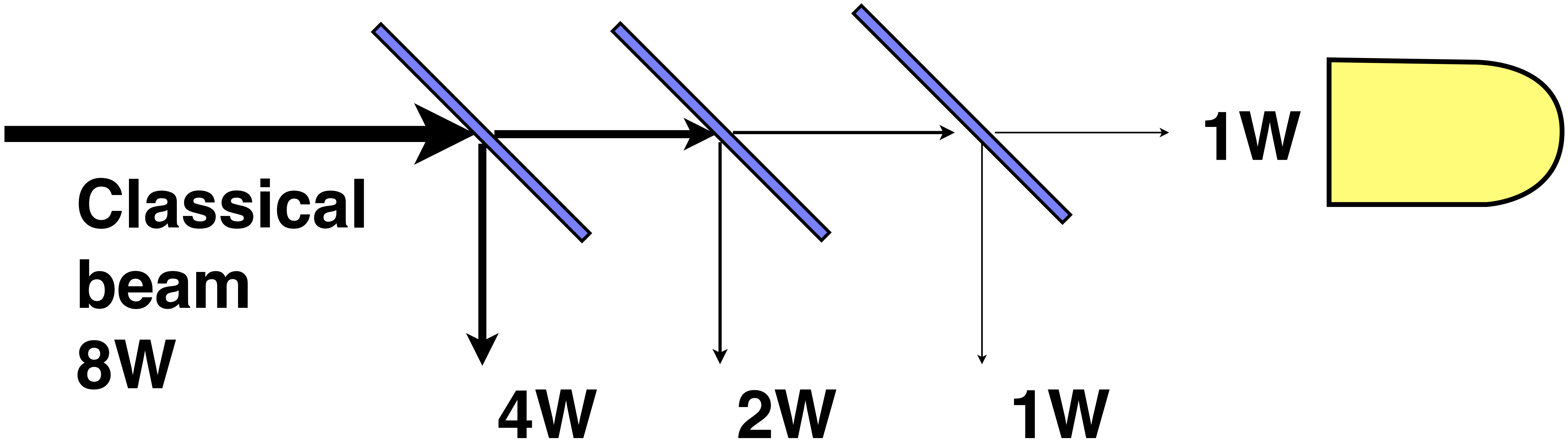
With 50% probability we see:



With 50% probability we see:



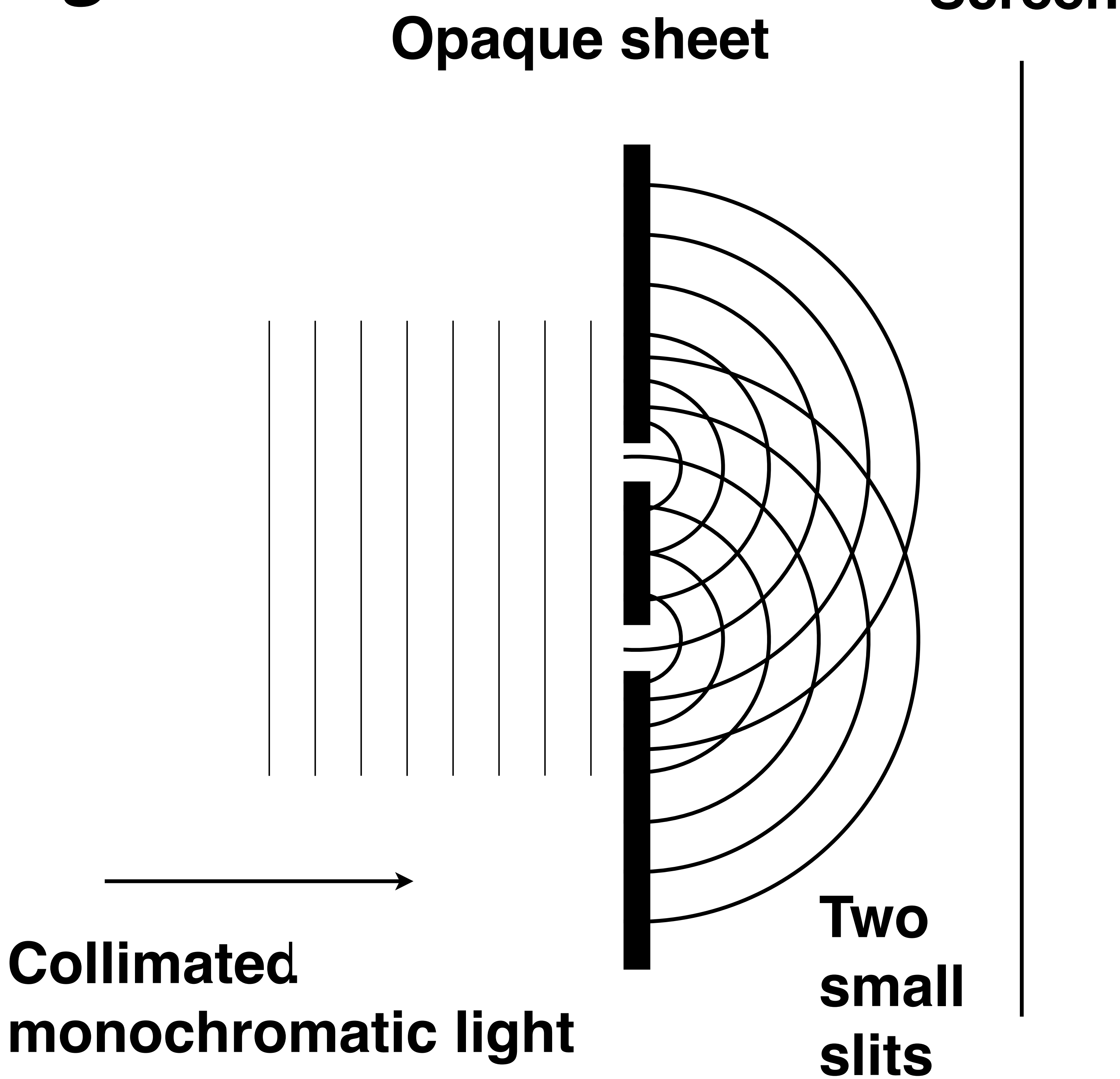
Quiz



– 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%

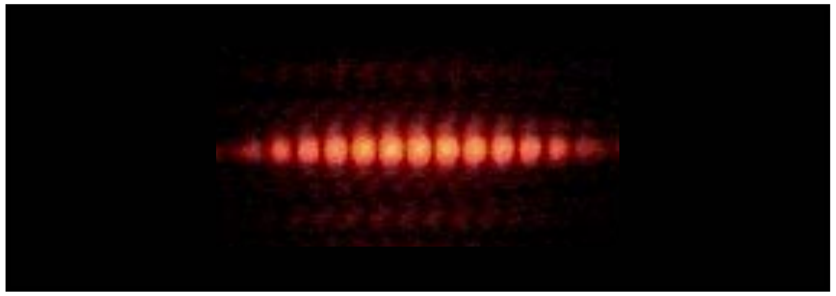
The Young Two-slit experiment

With classical light:



T. Young

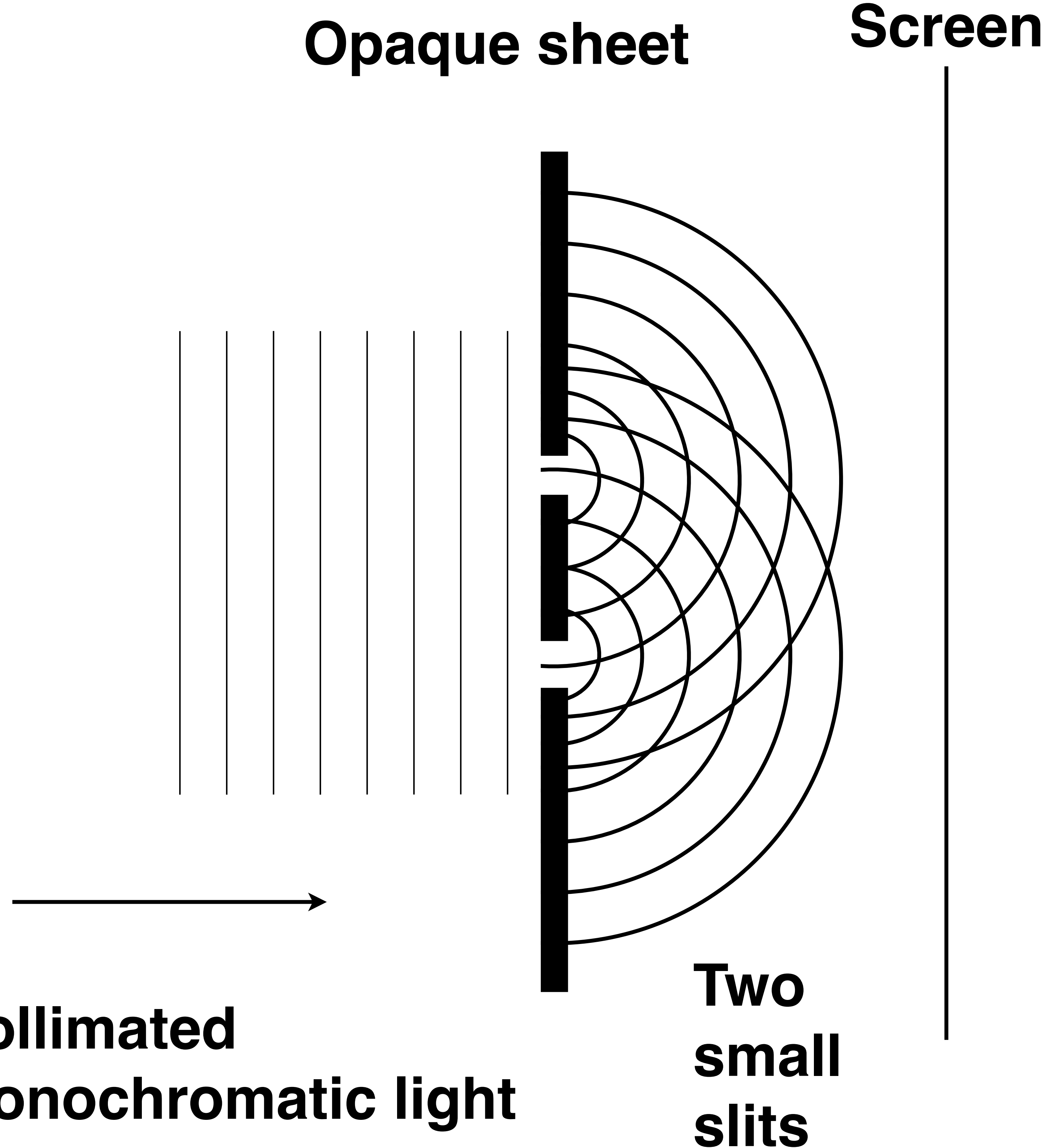
What we observe on the screen



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.

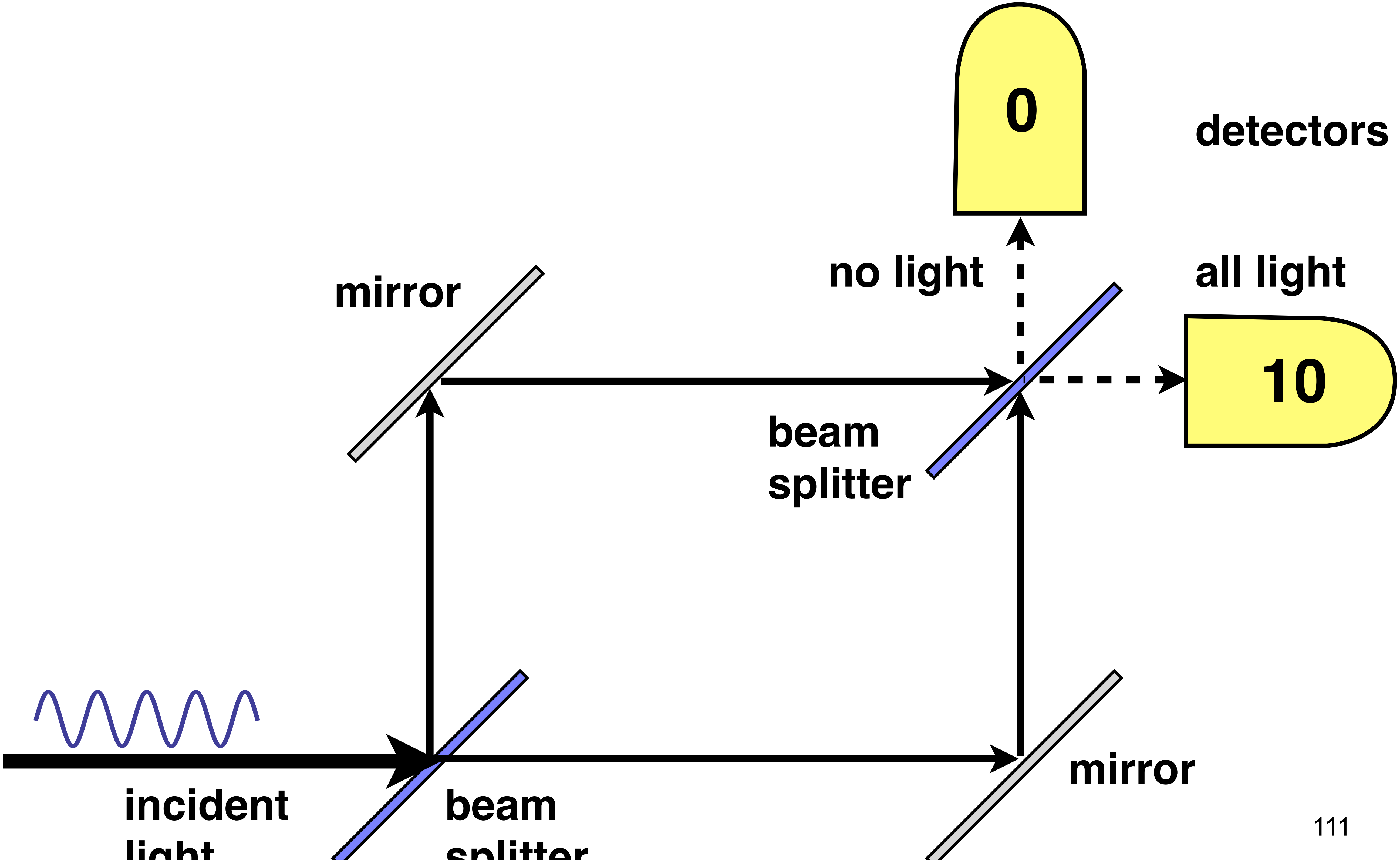
Universiteit Leiden

0,025 msec

Mach-Zehnder Interferometer

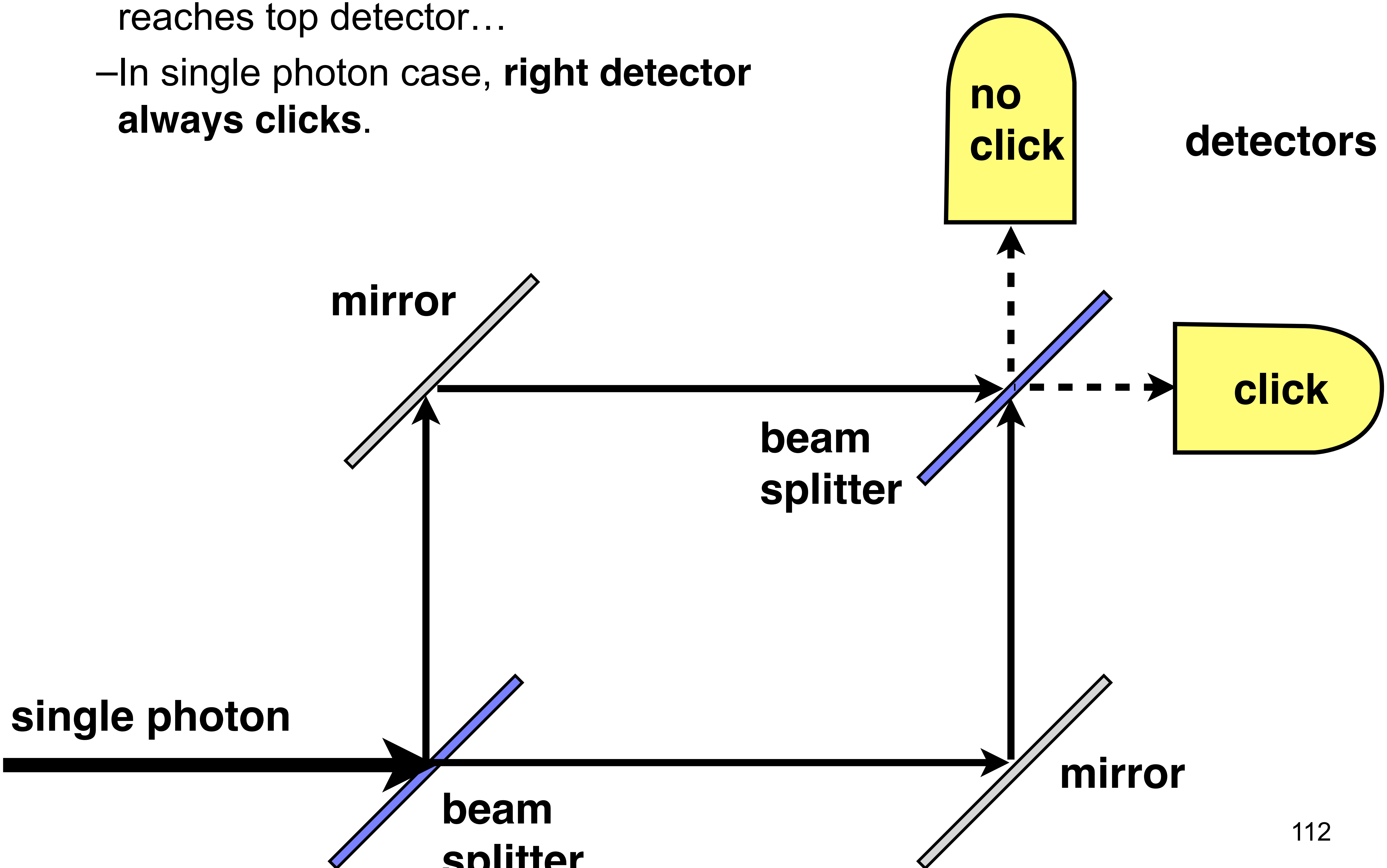
–Now let's consider single photons in the Mach-Zehnder interferometer.

–With classical light, all light exits to the right detector.



Mach-Zehnder interferometer

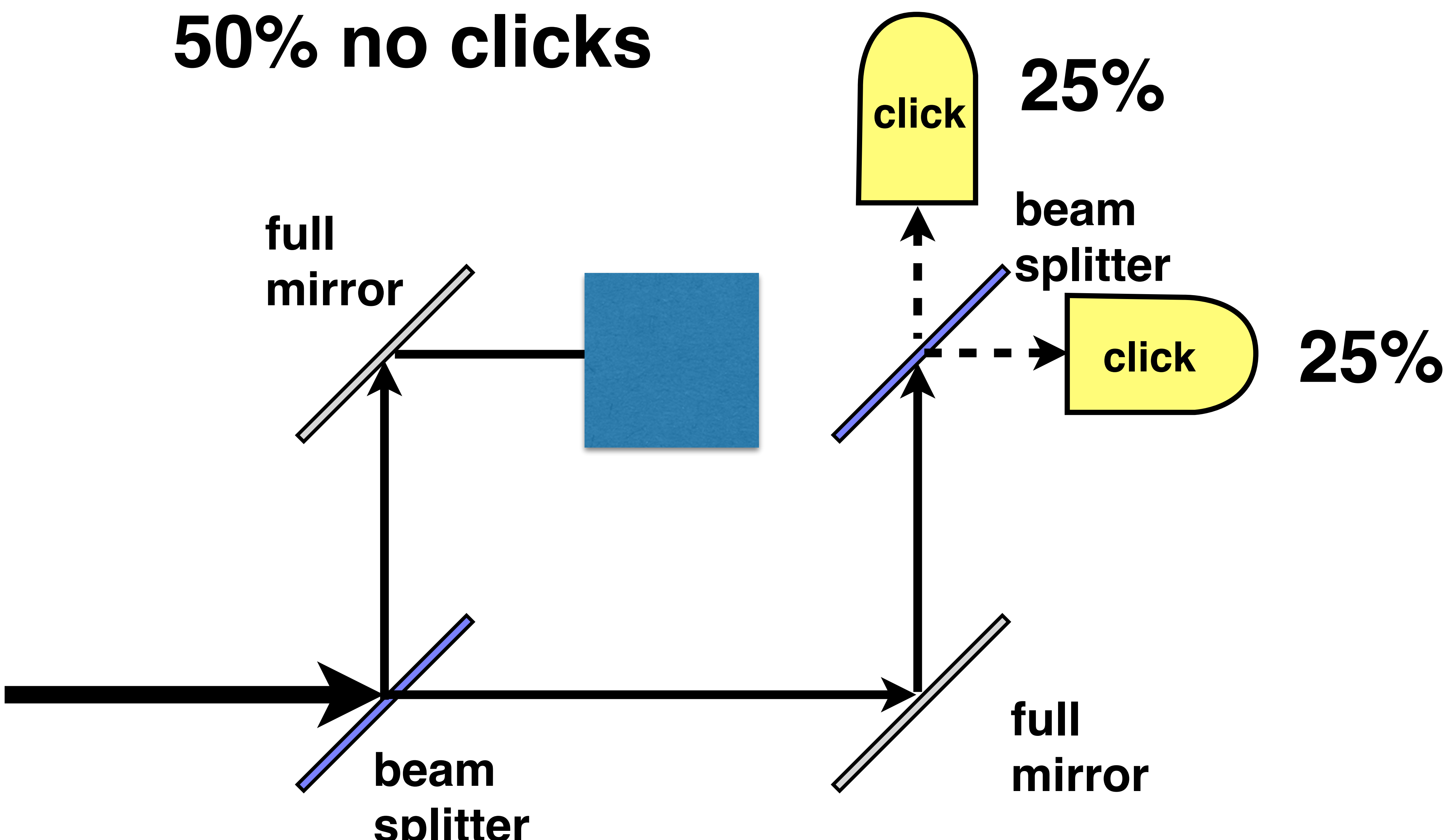
- –We apply the probability rule:
- –Since, in classical case all **intensity** reaches top detector…
- –In single photon case, **right detector always clicks**.



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**.

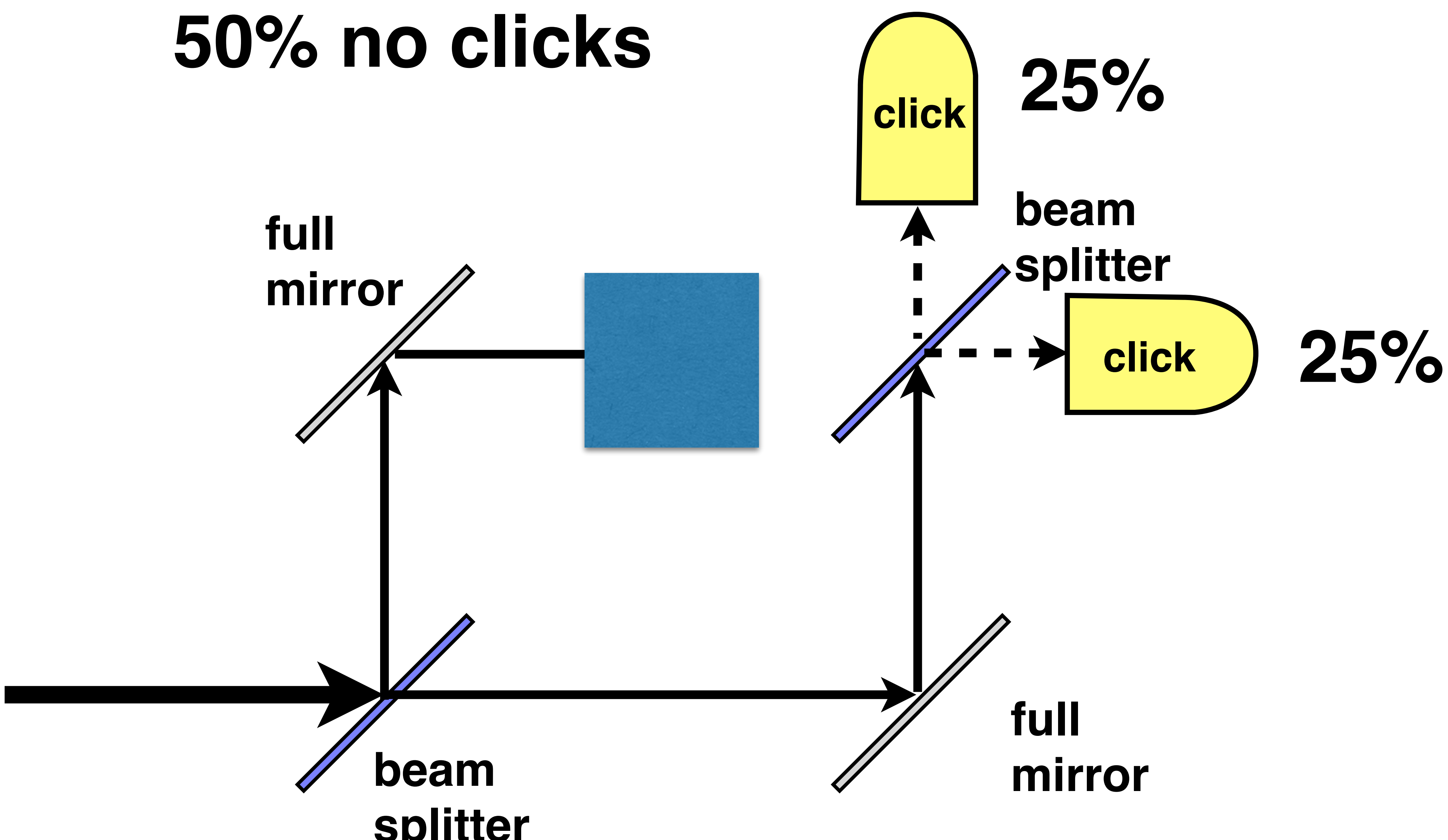


Wave-particle duality of the photon

–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.

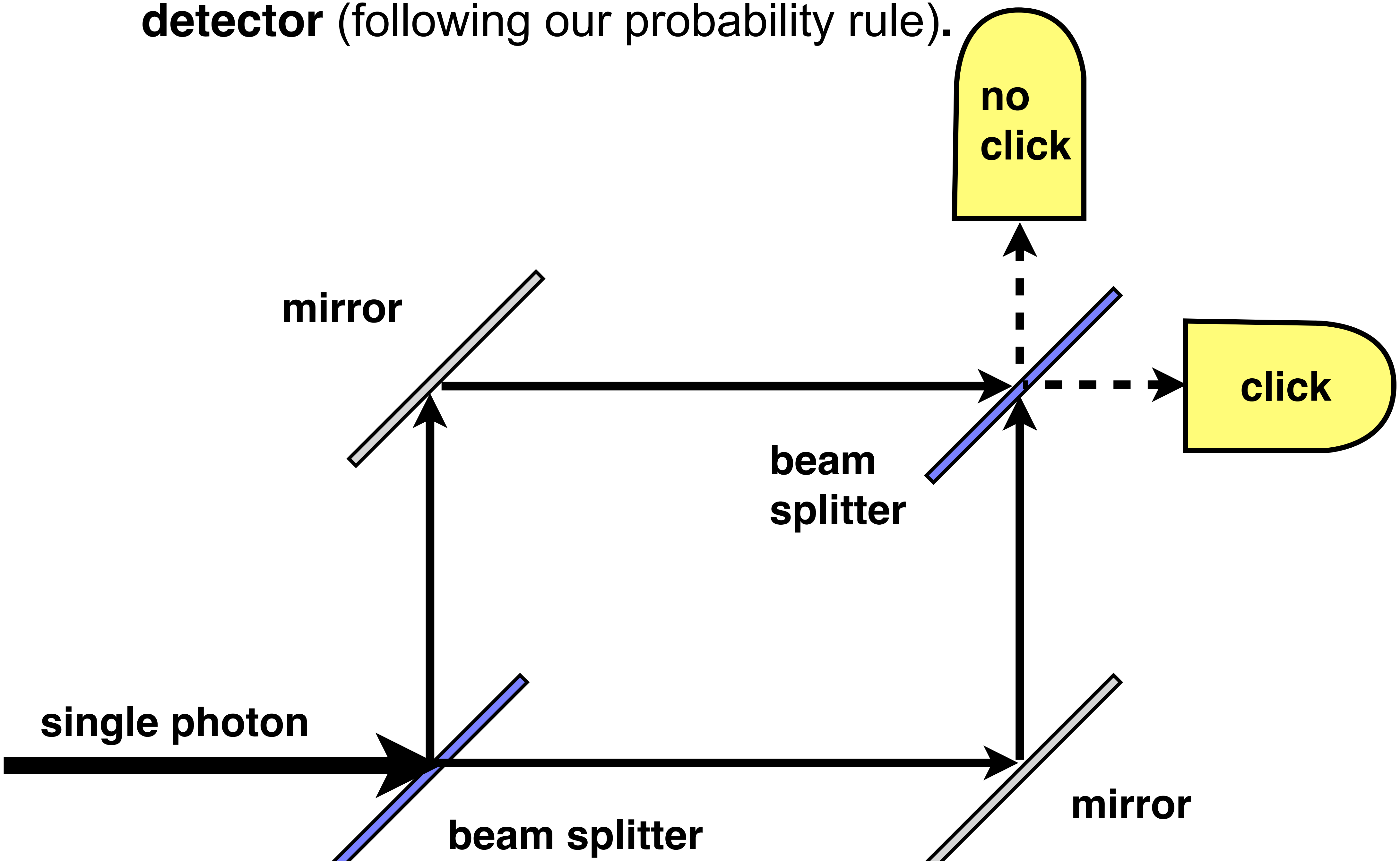


Wave-particle duality of the photon

–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).

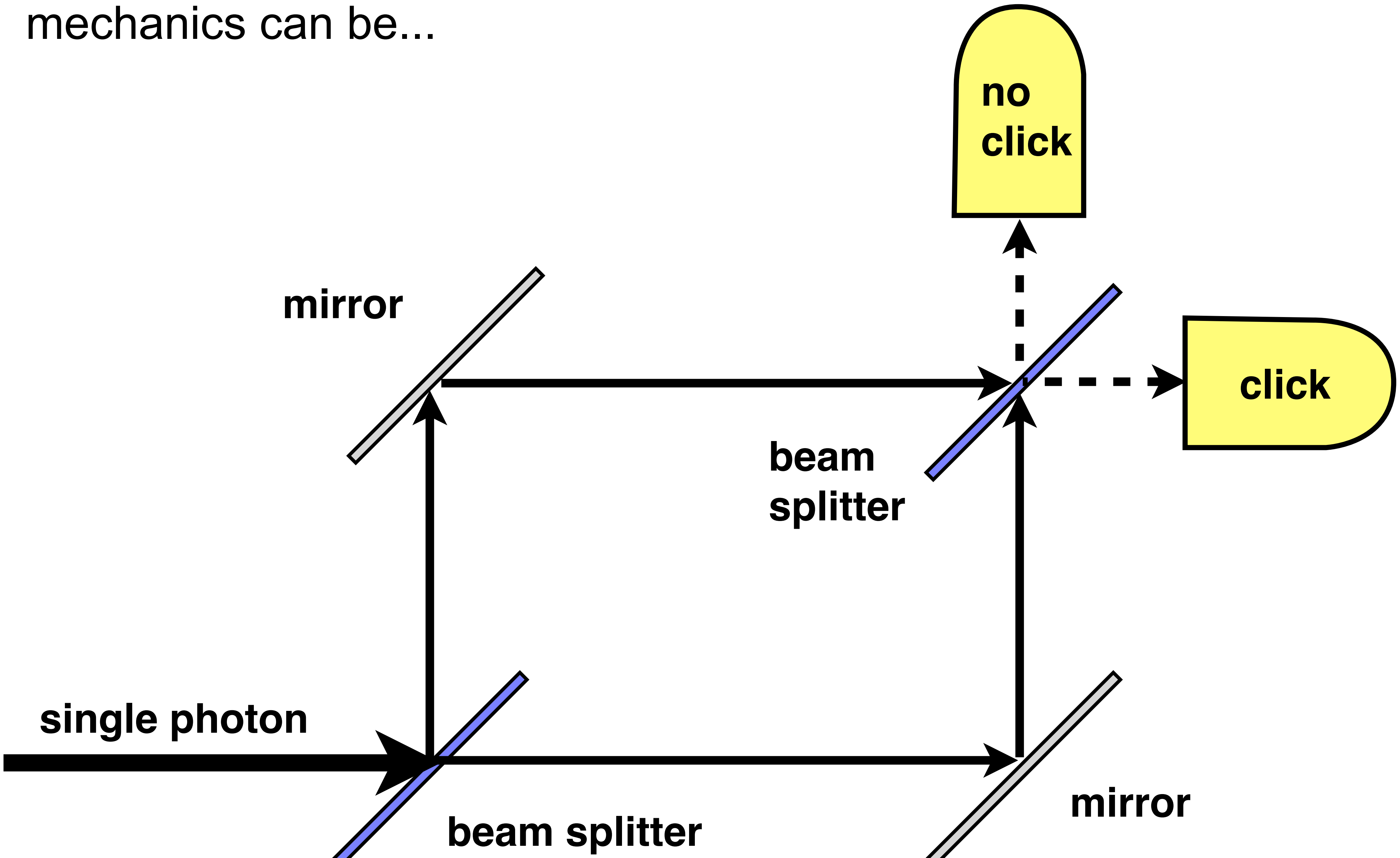


Measurement in quantum physics

–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: $E = hf$

- 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.