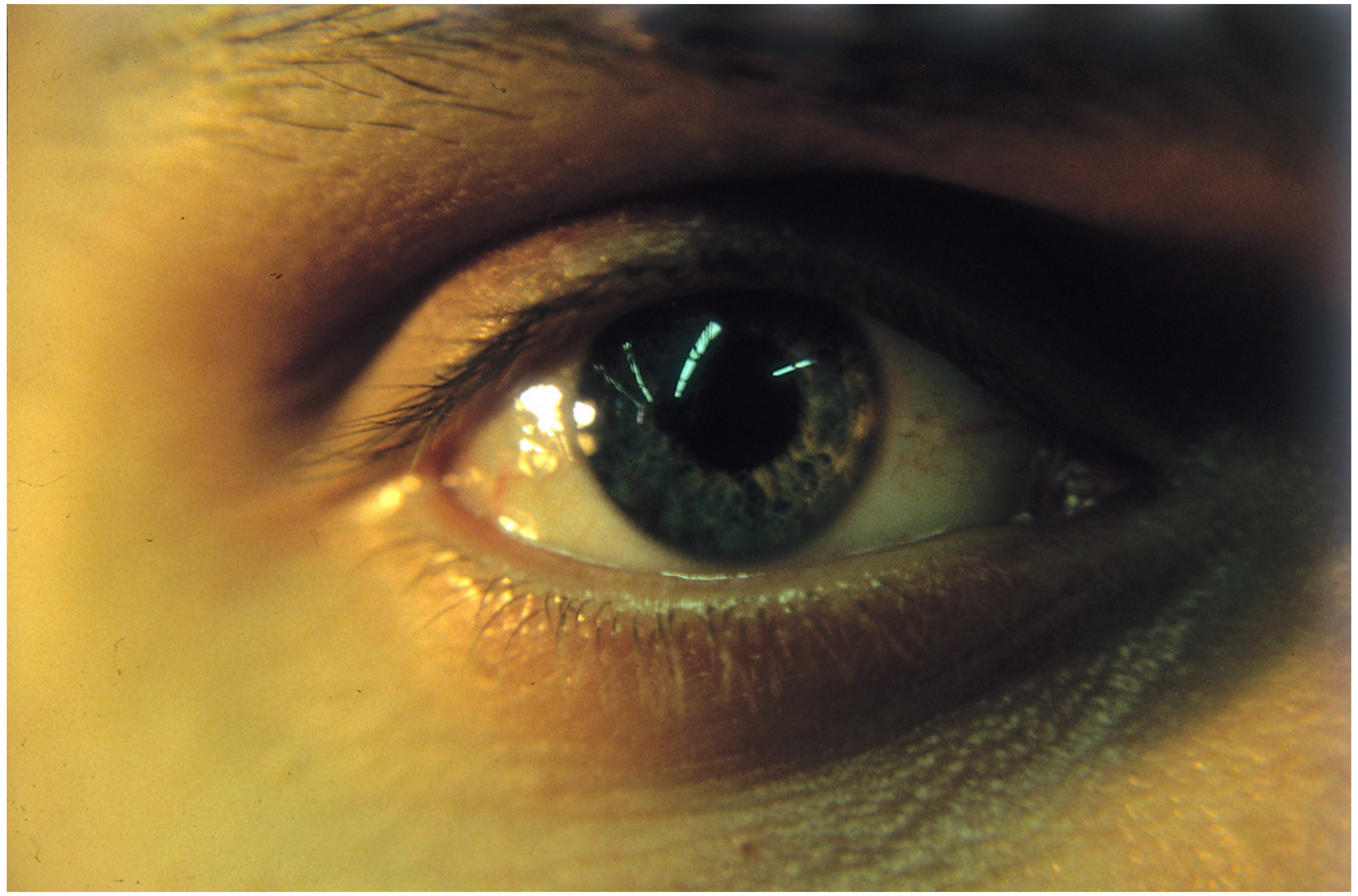
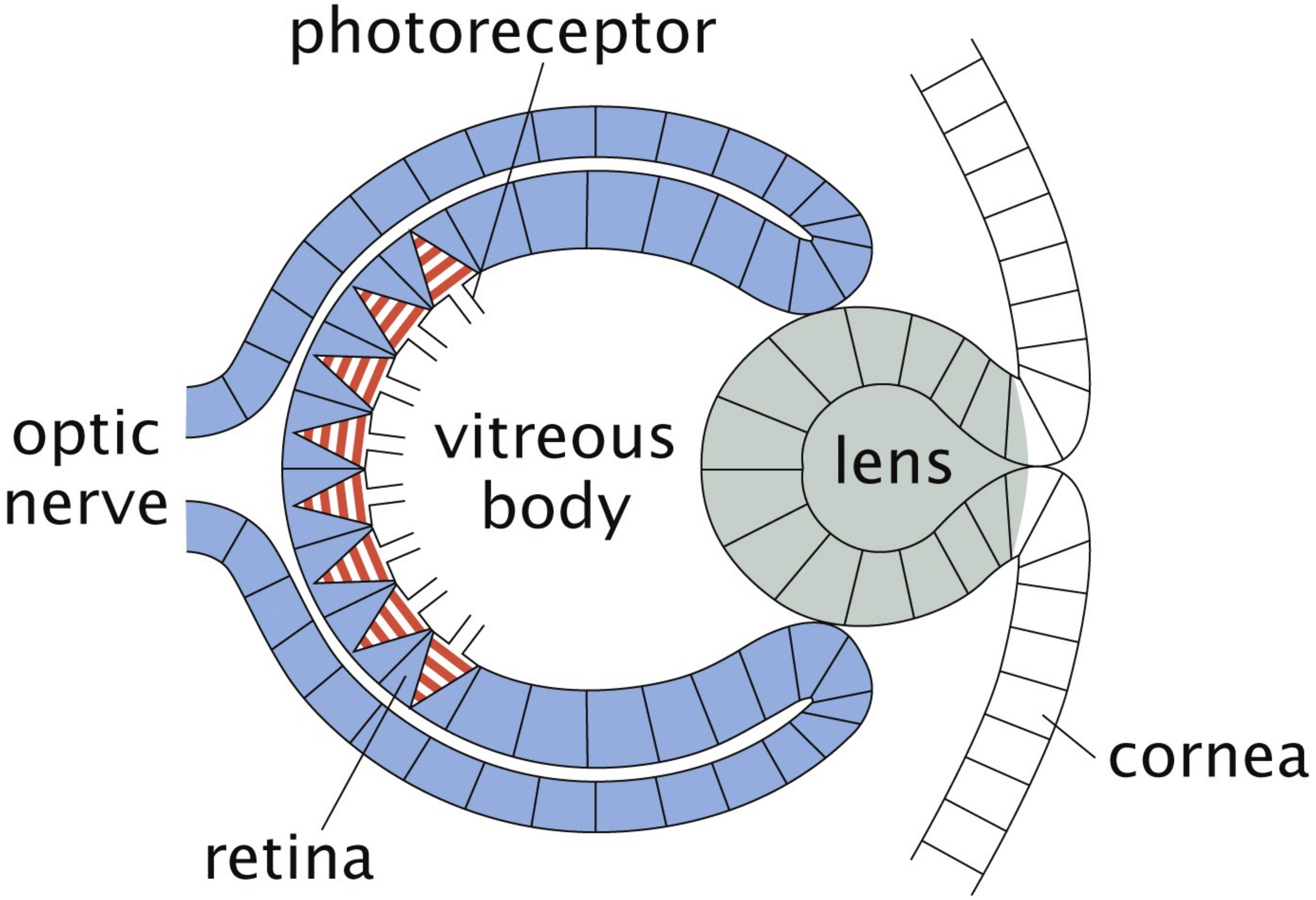
Eye vision: how biology has made a quantum detector that can detect single photons!

A peep into the biology and engineering of vision





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Can we design experiments to test whether eyes are indeed single photon detectors?

In India, many students get high marks, first rank and gold medals!

But most of them do not go on to make important science/engineering discoveries!

Why?

Getting mark is relatively easy;
You learn to answer questions

Difficult thing is to make/find good questions!

To make questions that can be solved and the solution will have non-trivial consequence!

Research is: finding questions and solving them. No one will give you questions. You have to be curious!

The question you choose has to be tractable and non-trivial

The best way to have new unsolved non-trivial questions is to read research papers

Research papers present the latest knowledge

They will point you towards unanswered questions!

Research papers present the latest knowledge

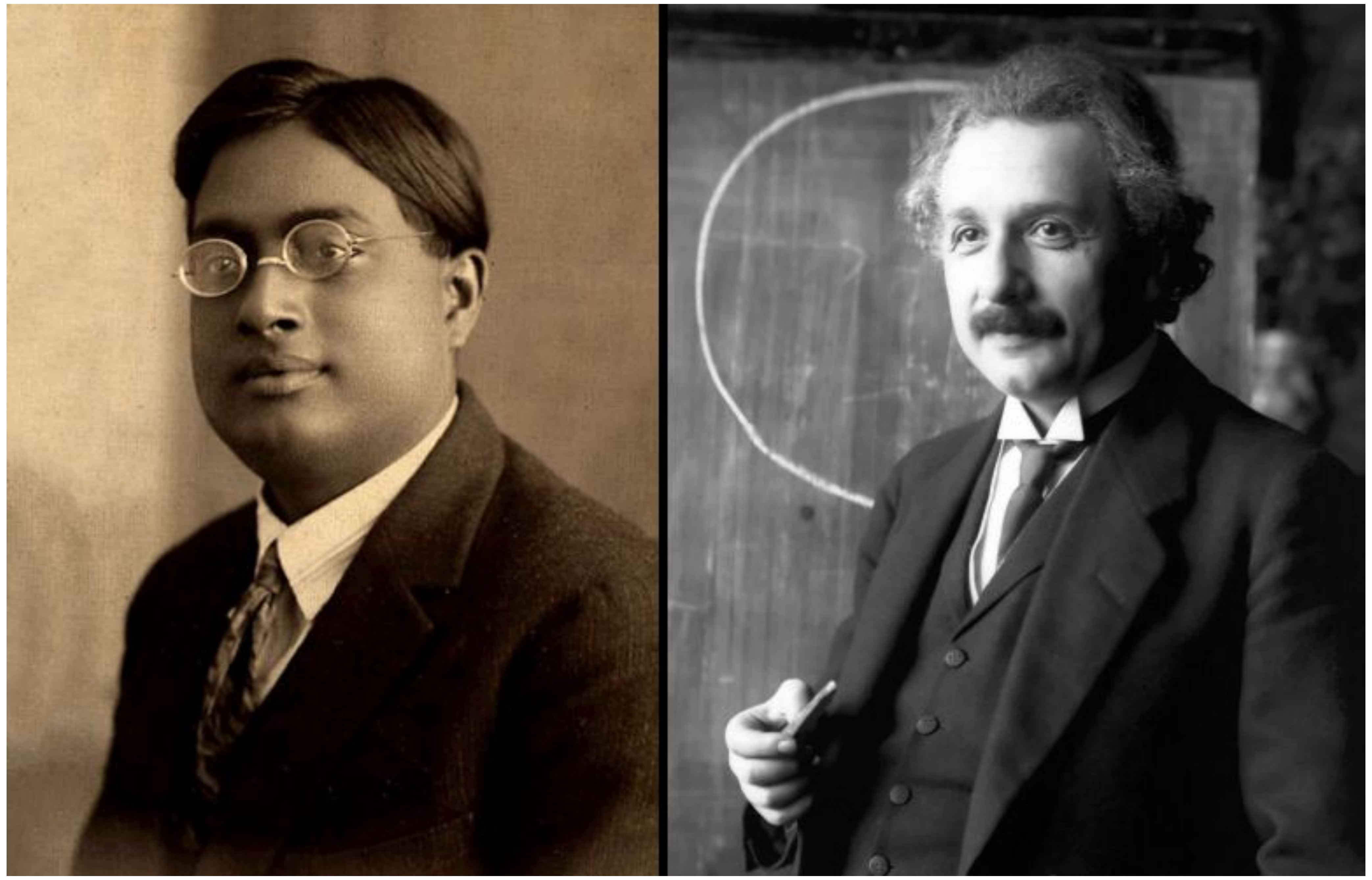
Satyendra Nath Bose: A teenager from Kolkata who used to read research papers

ছাত্রাবস্থায় সত্যেন্দ্রনাথ (১৯১০-১১)
Student Satyendranath (1910-11)

As a teenager, he read Einstein’s papers on photons and other papers

While reading he realised: to deal with a collection of photons one has to apply some rules of statistics;

If I take known ideas and apply rules of statistics, something non-trivial arises

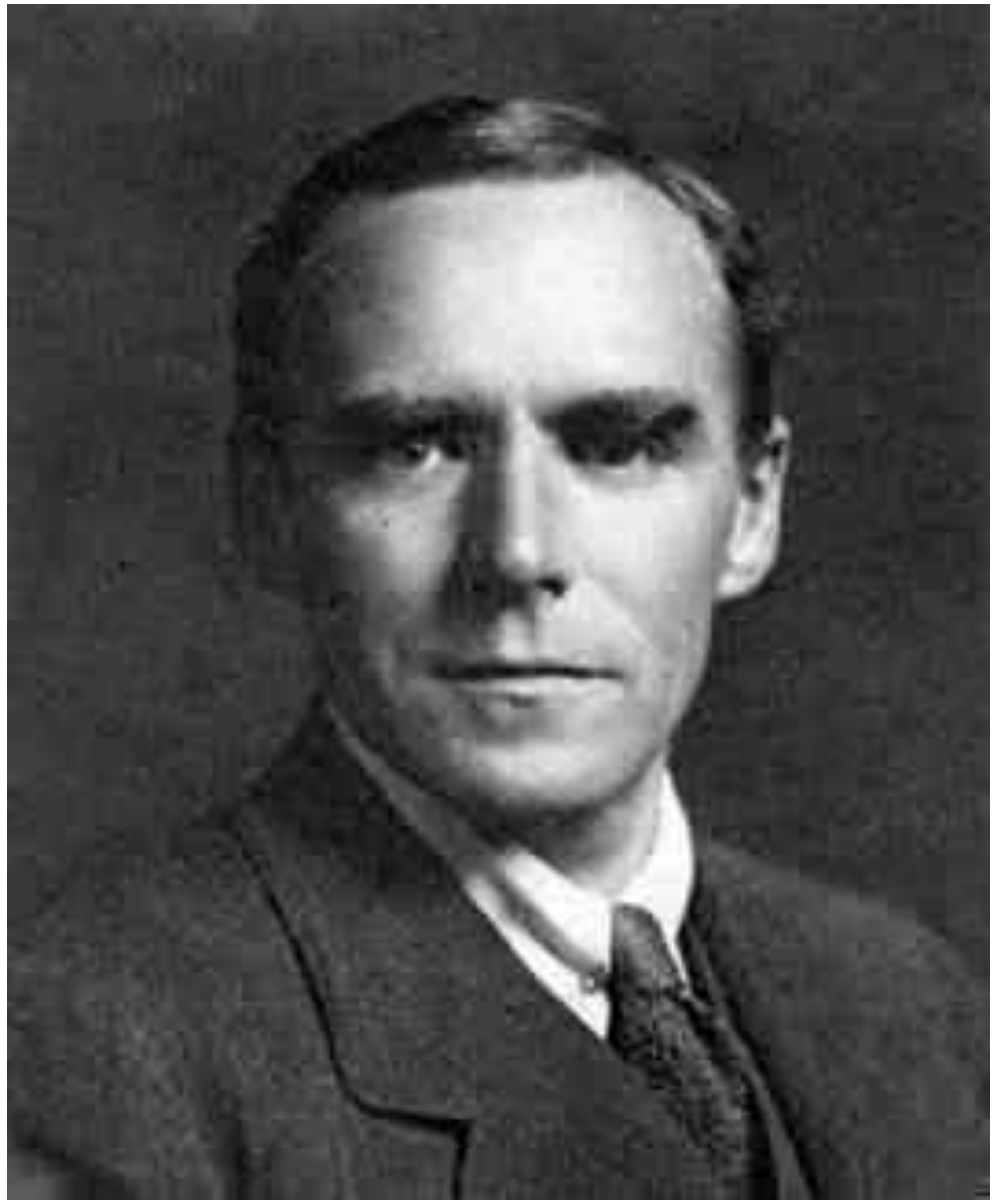


Photons obey statistical rules discovered by Satyendra Nath Bose.

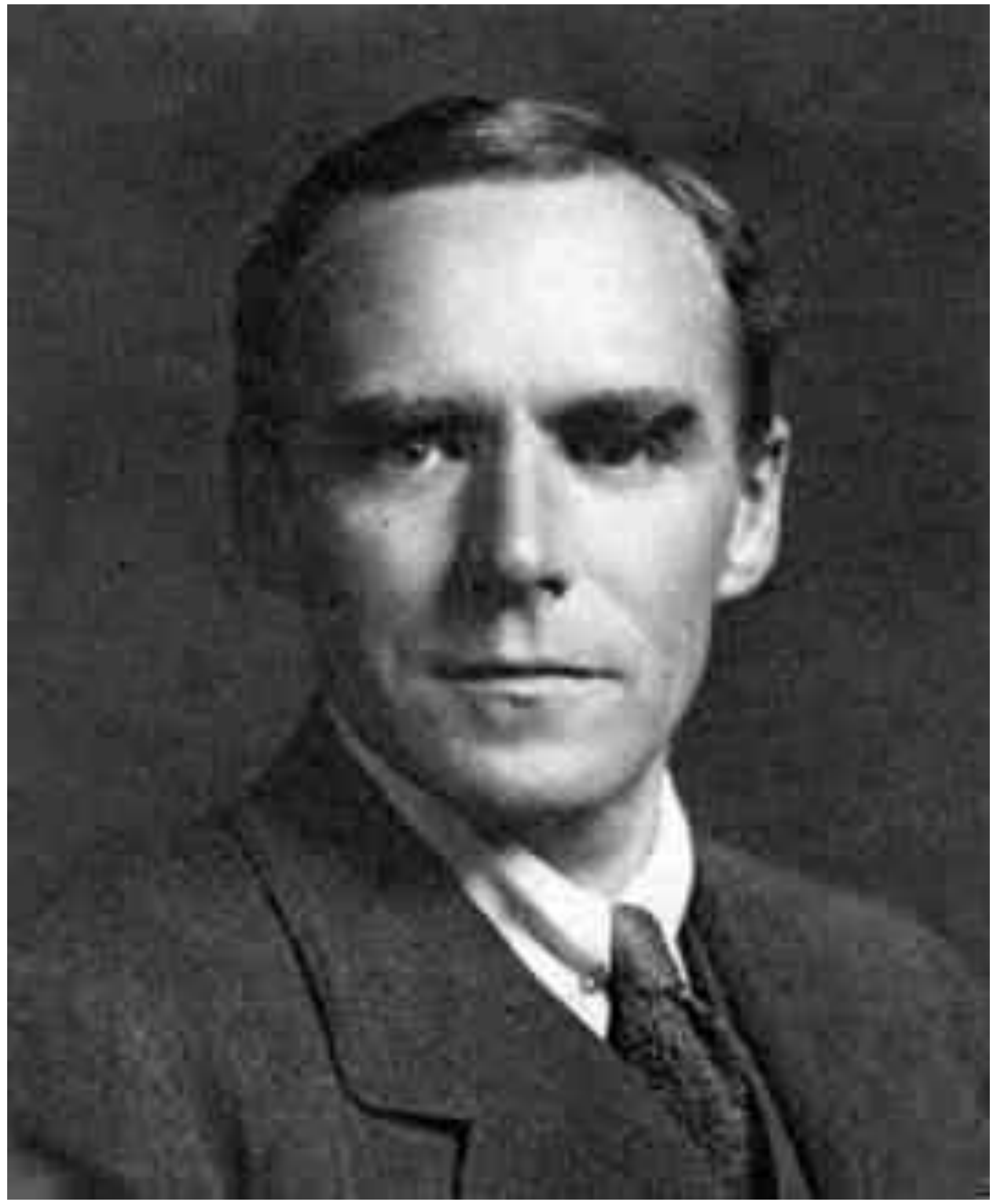
(Einstein extended it to other cases)

Bose-Einstein statistics: How likely to find photons and other similar particles (known as bosons) in a particular energy state

Story of an Undergraduate project



Story of an Undergraduate project

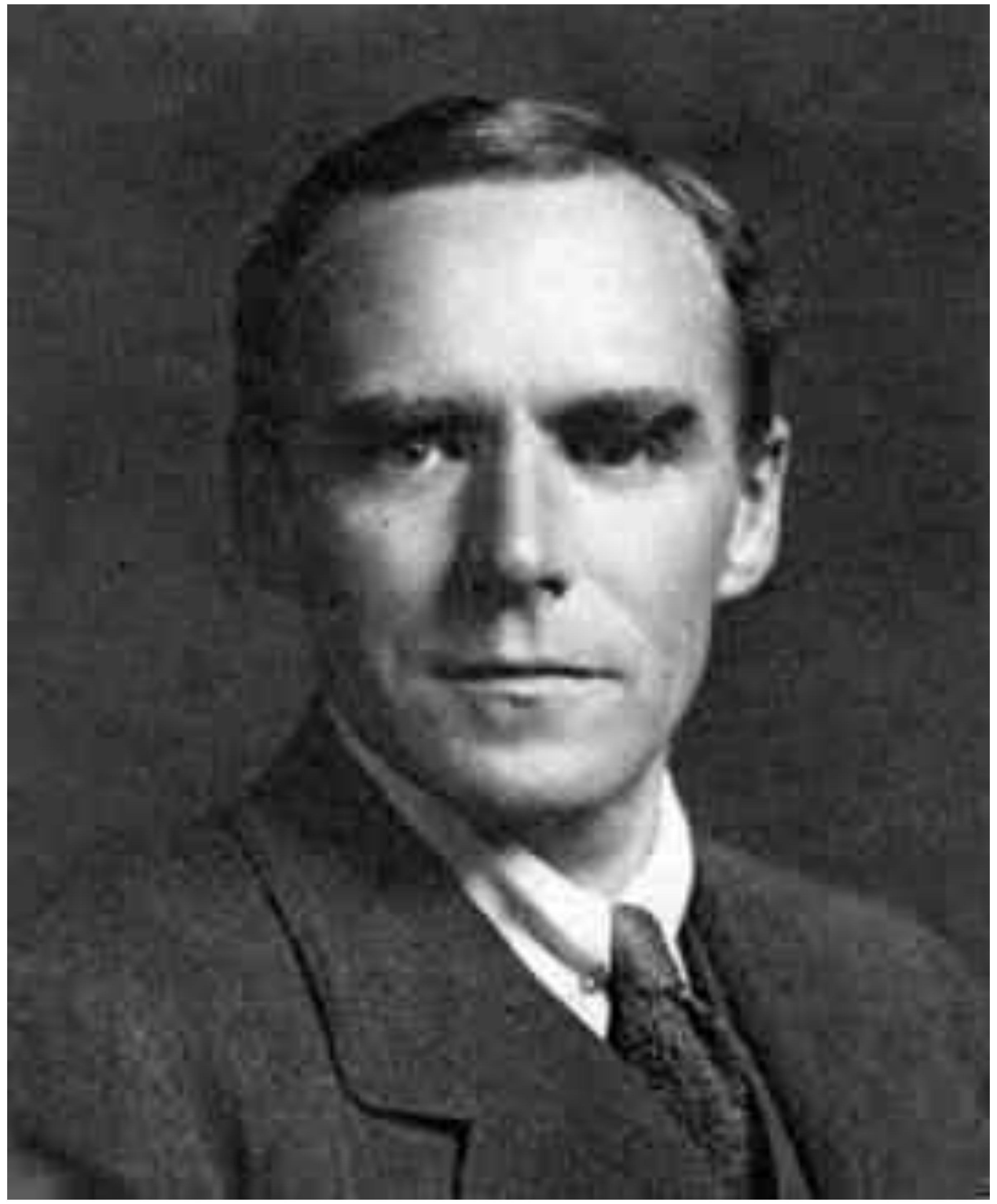


1908: GI Taylor was an undergraduate student.

He went beyond textbooks; read research papers about the “interference” of light

He was curious how feeble a light can show interference

UG project by Taylor



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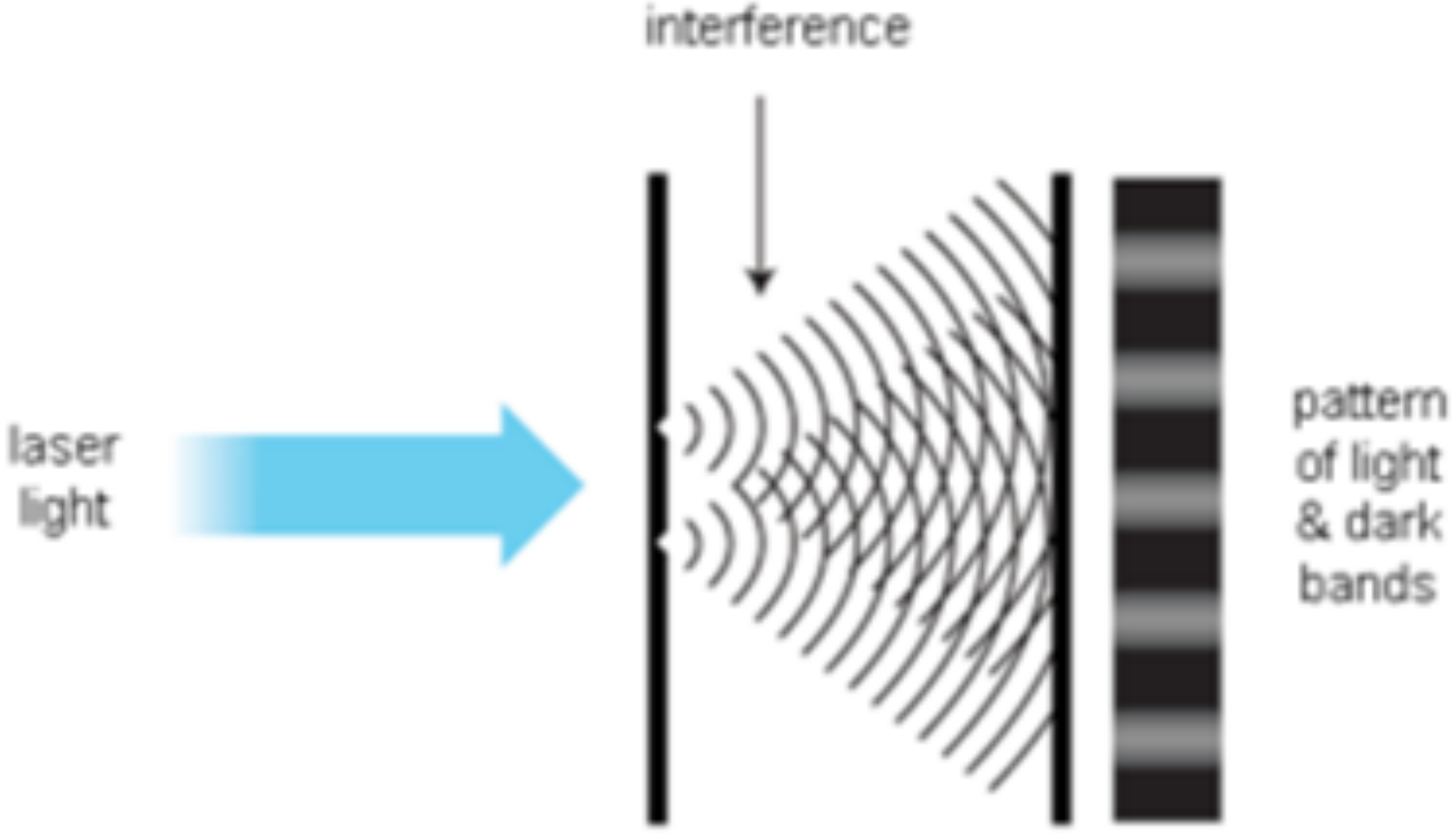
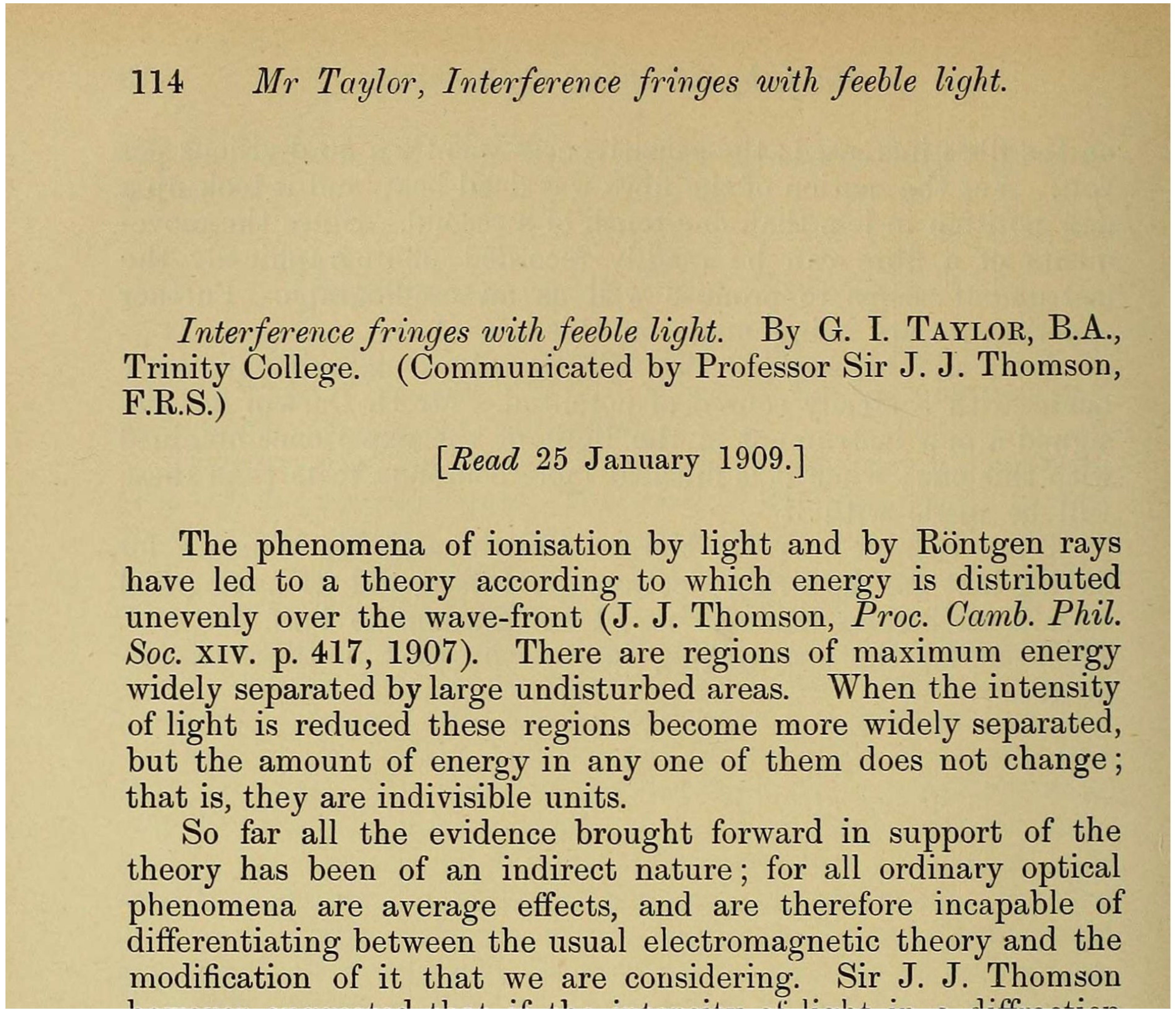


Taylor's UG project



Interference fringes with feeble light. By G. I. TAYLOR, B.A., Trinity College. (Communicated by Professor Sir J. J. Thomson, F.R.S.)

[*Read* 25 January 1909.]

The phenomena of ionisation by light and by Röntgen rays have led to a theory according to which energy is distributed unevenly over the wave-front (J. J. Thomson, *Proc. Camb. Phil. Soc.* XIV. p. 417, 1907). There are regions of maximum energy widely separated by large undisturbed areas. When the intensity of light is reduced these regions become more widely separated, but the amount of energy in any one of them does not change; that is, they are indivisible units.

So far all the evidence brought forward in support of the theory has been of an indirect nature; for all ordinary optical phenomena are average effects, and are therefore incapable of differentiating between the usual electromagnetic theory and the modification of it that we are considering. Sir J. J. Thomson

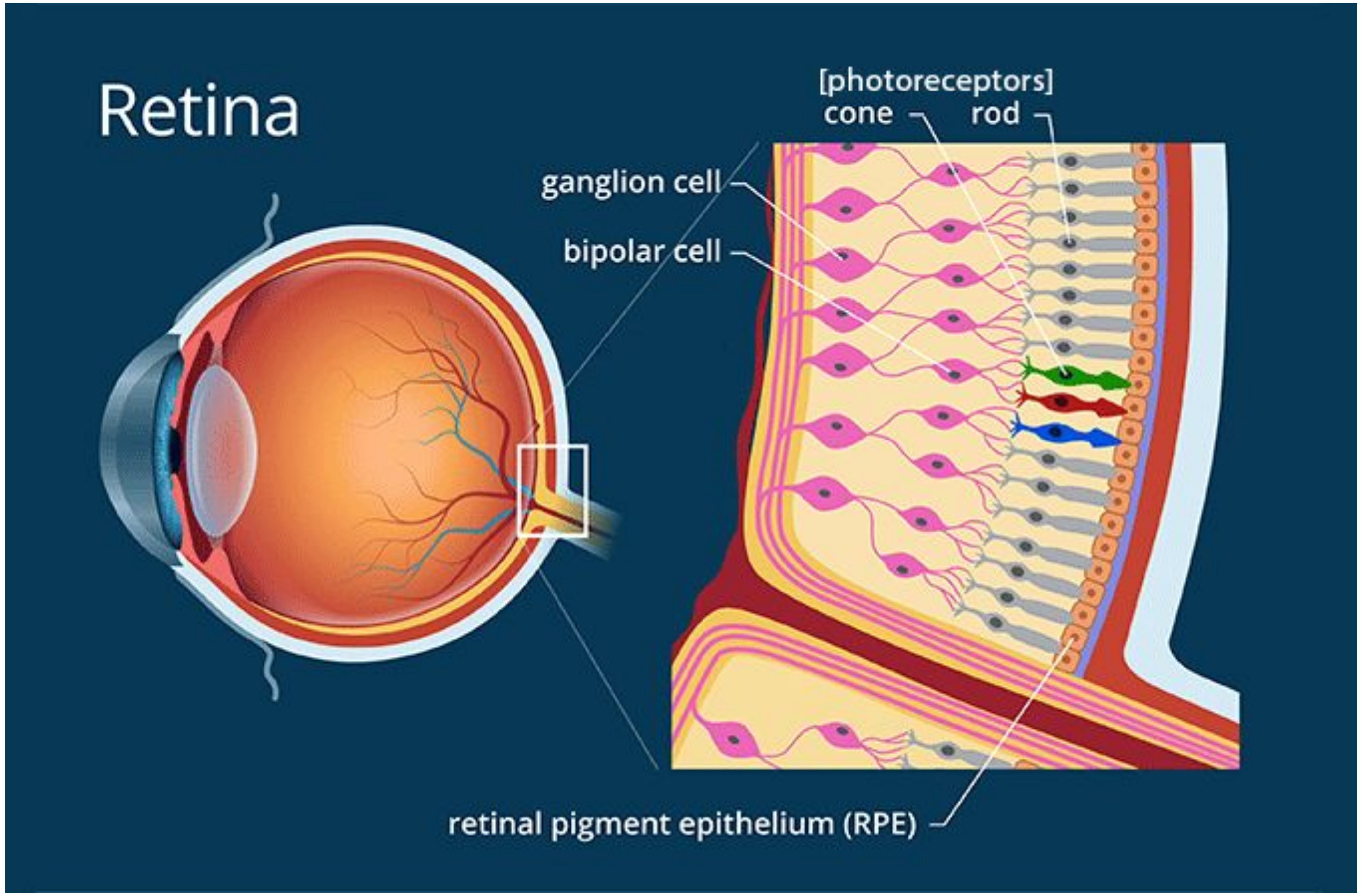
- Taylor set up an experiment in dark room somewhere in a basement
- He set up slits and gas light source
- Intensity of light were adjusted by placing smoked glass screens
- Measured interference /diffraction of a needle
- Very low intensity: exposure = 3 months!
- Corresponds to single photons!

He found interference patterns => This implies single photons can show interference patterns!

Photons can be wave and particle = quantum mechanics!

How does our eye detect light?

Is it detecting a quantum mechanical particle = single photon?



"Rod" cells do the work when light intensity is low (night vision!)

Cone cells do the work when light intensity is high. They detect colour

Simple experiment to detect whether our eye cells would detect single photons

- Sit in a dark room
- Send low intensity light pulse for a short duration dt
- Answer the question: can your eyes detect the light? YES or NO
- Repeat the experiment several times
- Analyse the statistics

Certain amount of light of intensity I = a few photons

- Small intensity light = a few photons falling into the detector in our eyes
- How many photons?
- Average number of photons falling in our eye is proportional to intensity
  Intensity, $I \propto M$ photons on an average
- Average number of photons falling in eye, $M = aI$
- More the intensity, more the number of photons falling in our eyes

Photons falling is a probabilistic process

- Consider photons falling as like radio active decay
- Classical analogy: a bunch of mangoes randomly falling
- Sit under a mango tree and answer: What is the probability that exactly n mangoes will fall in the next hour if the M was the average number of mangoes falling (per hour)?
-

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- **Poisson distribution**

Sit under a mango tree and answer: What is the probability that exactly n mangoes will fall in the next hour if the M was the average number of mangoes falling (per hour)?

$$P(n, M) = \frac{M^n \exp(-M)}{n!}$$

Poisson distribution

What is the probability of exactly n photons falling, if the average number is M?

In a dark room with feeble flash of light: What is the probability that exactly n photons will fall in the next flash if M was the average number of photons falling (per flash)?

$$P(n, M) = \frac{M^n \exp(-M)}{n!}$$

Poisson distribution

Simple experiment to detect whether our eye cells would detect single photons

- Sit in a dark room
- Send low intensity light pulse for a short duration dt
- Answer the question: can your eyes detect the light? YES or NO
- Repeat the experiment several times
- The answer YES means **at least** a detectable minimum number K photons fell in the eye. We have to find out what is K.

Probability of exactly n photons falling:

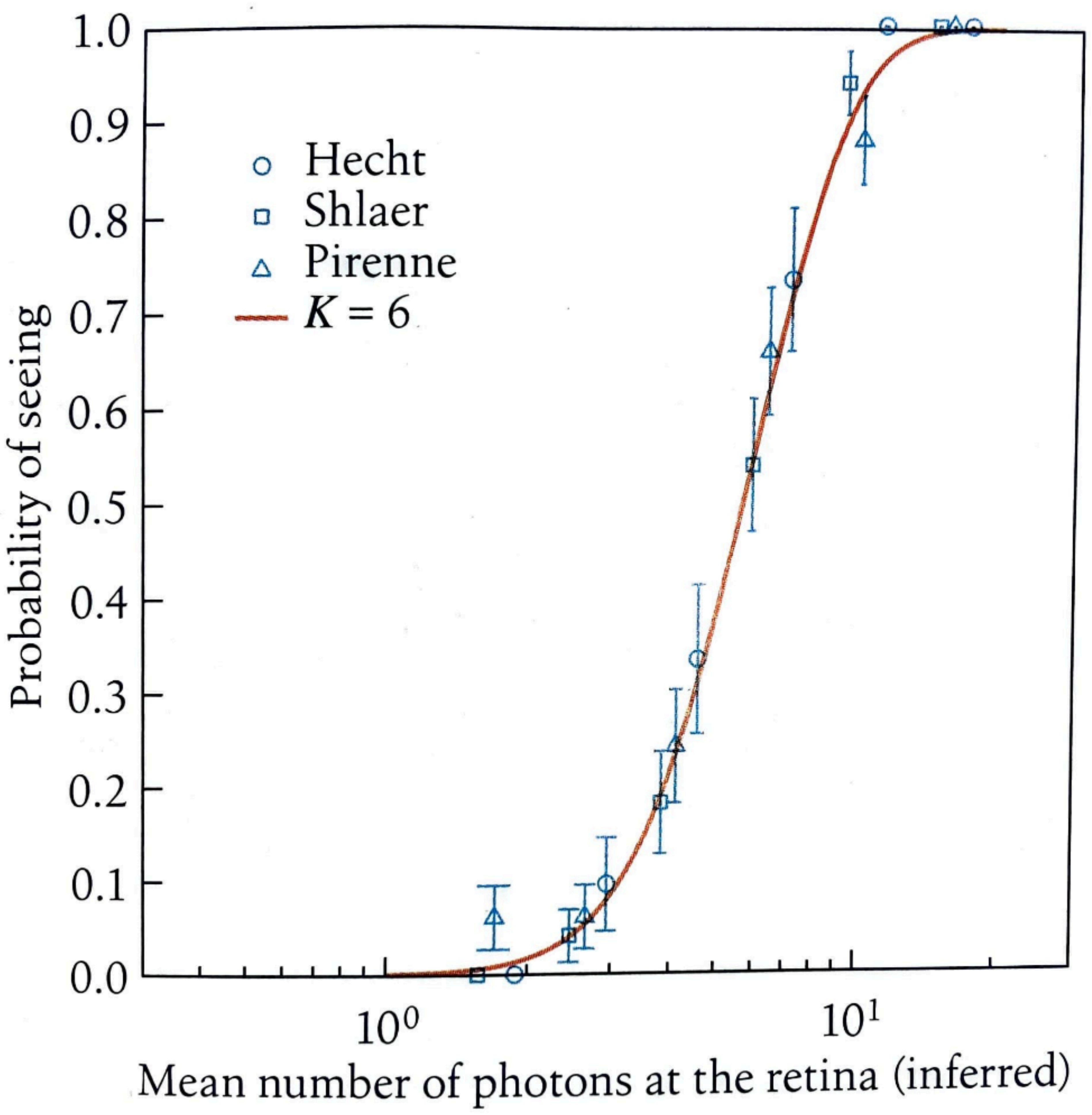
$$P(n, M) = \frac{M^n \exp(-M)}{n!}$$

Probability that number of photons is K or above:

$$P_{\text{cumulative}} = P_c = \sum_{n=K}^{\infty} \frac{M^n \exp(-M)}{n!}$$

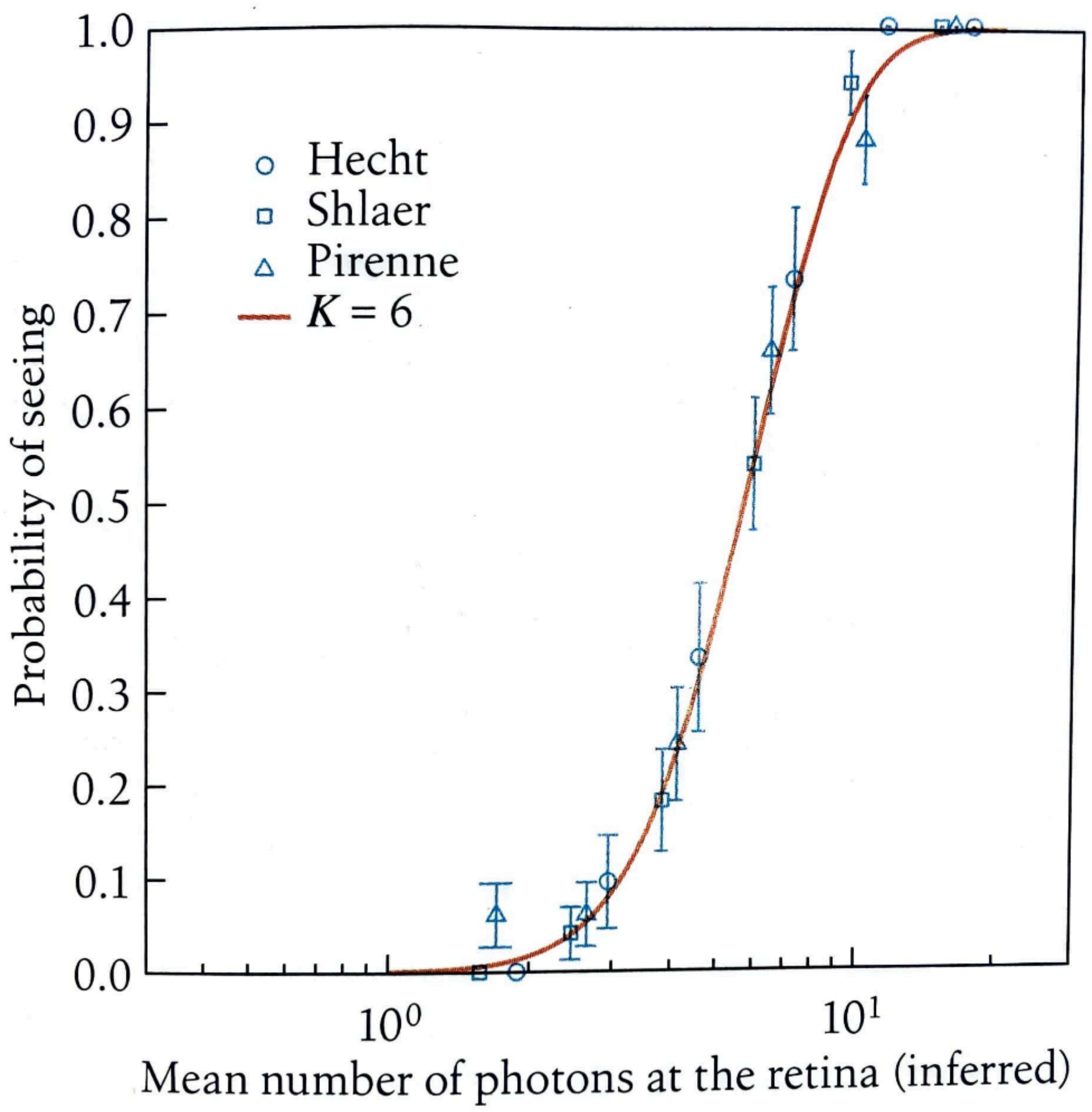
If you detect, you must have got k or above photons in your eye

Experiment: vary intensity of light (average number of photons) and ask did you see the flash of light or not



At high intensity, you will see light every time you repeat the experiment. Yes=100%

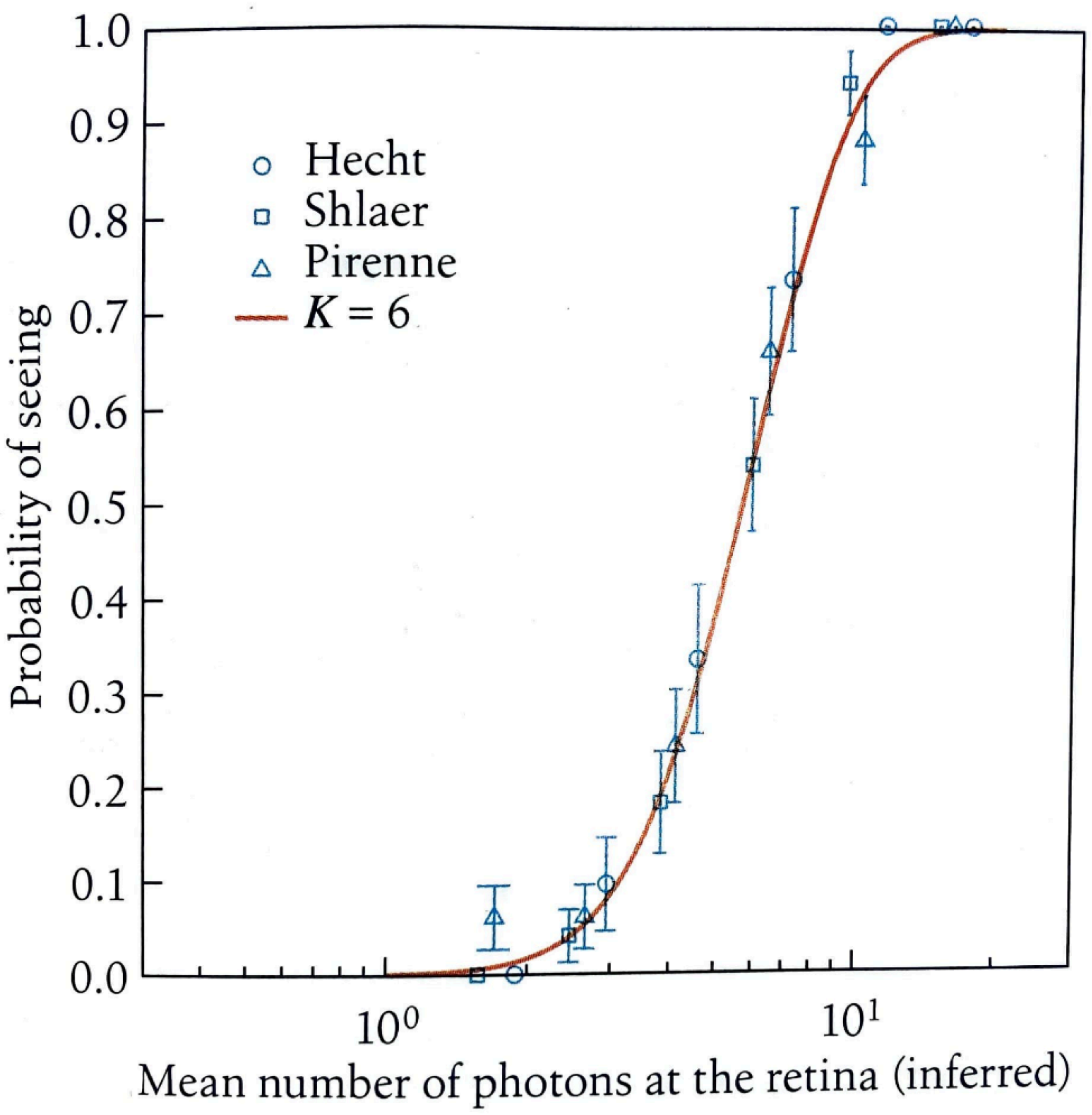
Experiment: vary intensity of light (average number of photons) and ask did you see the flash of light or not



At high intensity, you will see light every time you repeat the experiment. Yes=100%

At low intensity, you will NOT see light every time you repeat the experiment. Yes=10%

Experiment: vary intensity of light (average number of photons) and ask did you see the flash of light or not

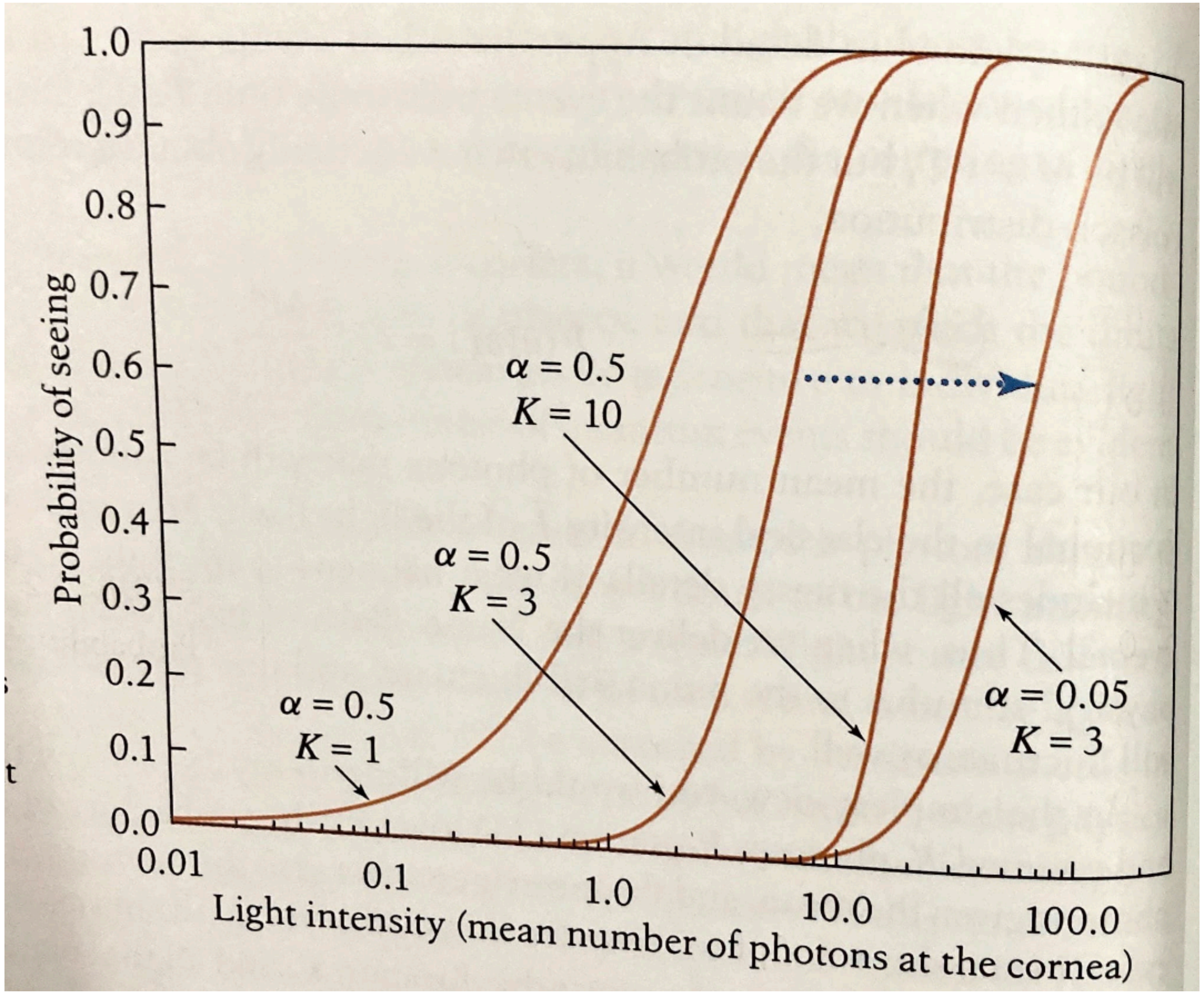


At high intensity, you will see light every time you repeat the experiment. Yes=100%

At low intensity, you will NOT see light every time you repeat the experiment. Yes=10%

$$P_{\text{yes}} = P_{\text{seeing}} = \sum_{n=K}^{\infty} \frac{M^n \exp(-M)}{n!}$$

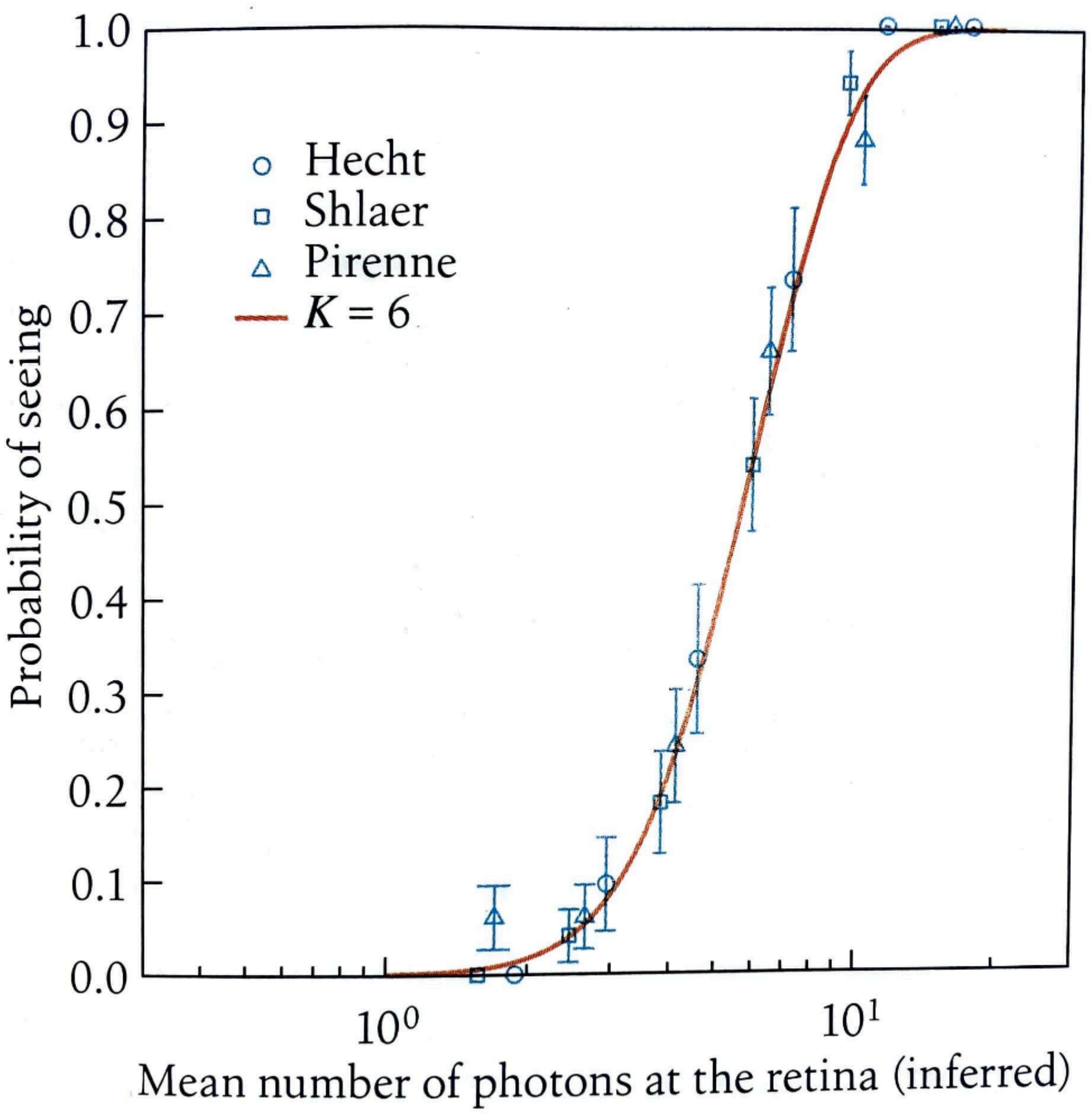
Intensity can be connected to mean number by varying a (alpha)



The curve either shifts to the right, or becomes more sharp in transition (slope changes)

Hence we can fit and get both the parameters K and a (=alpha in the figure)

Experiment: vary intensity of light (average number of photons) and ask did you see the flash of light or not



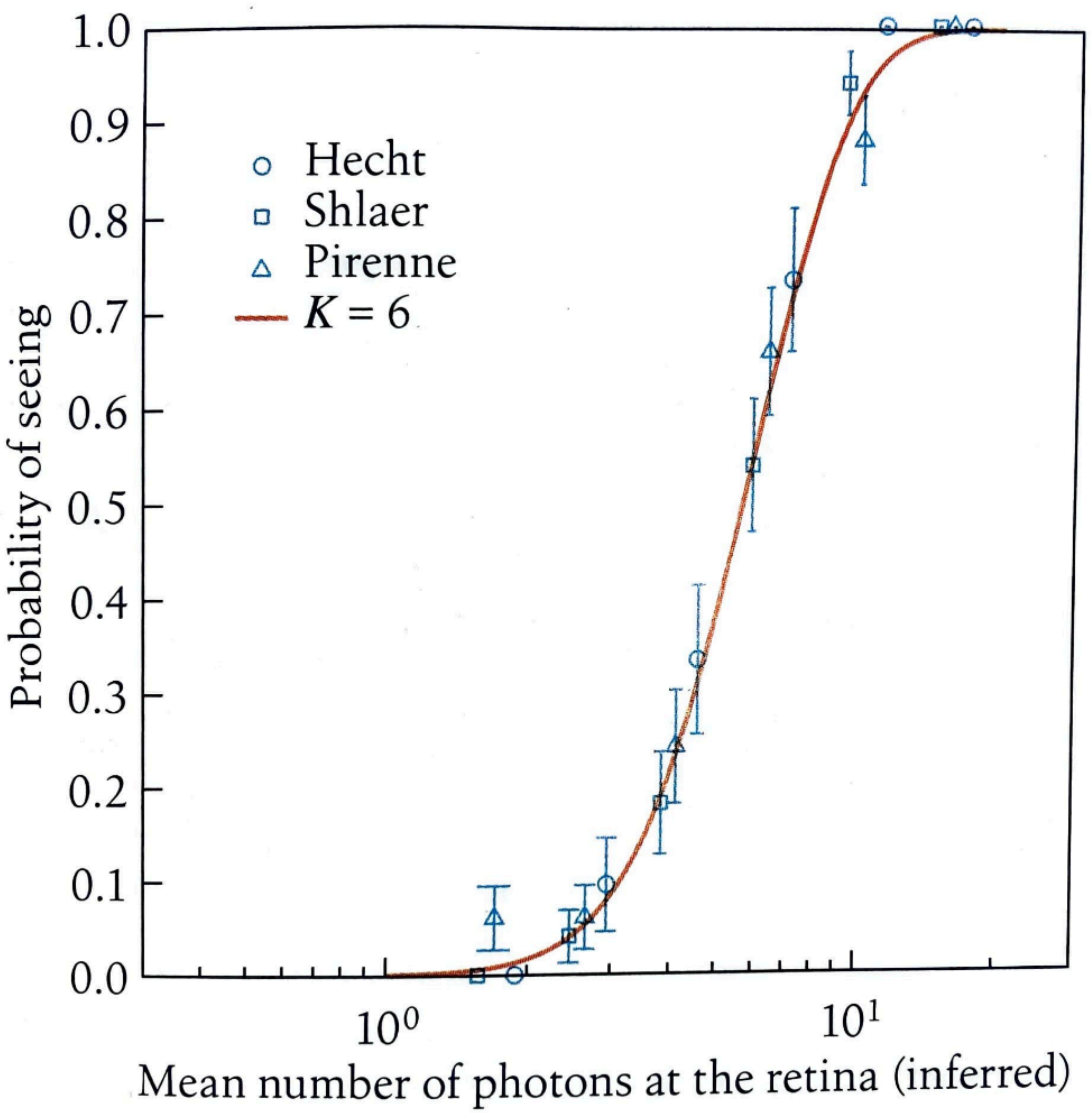
$$P_{\text{yes}} = P_{\text{seeing}} = \sum_{n=K}^{\infty} \frac{M^n \exp(-M)}{n!}$$

Only for one value of K, the curve will fit the data

Best fit K =6

six photons falling at low intensity

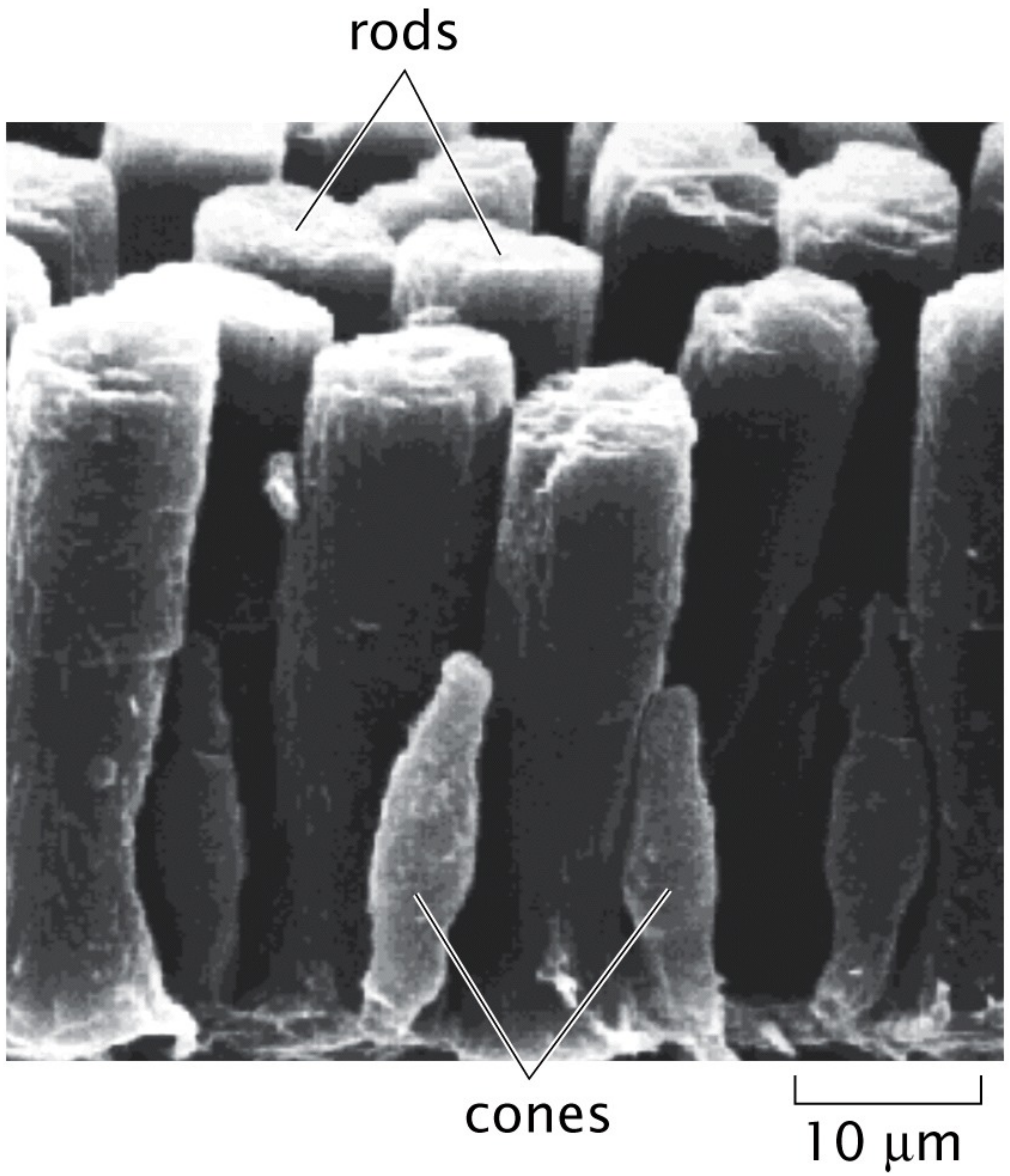
Six photons falling at low intensity



An eye has many many rod cells in retina; many more than six

This means: single photons per rod cell in the retina!

Two types of photo receptor cells



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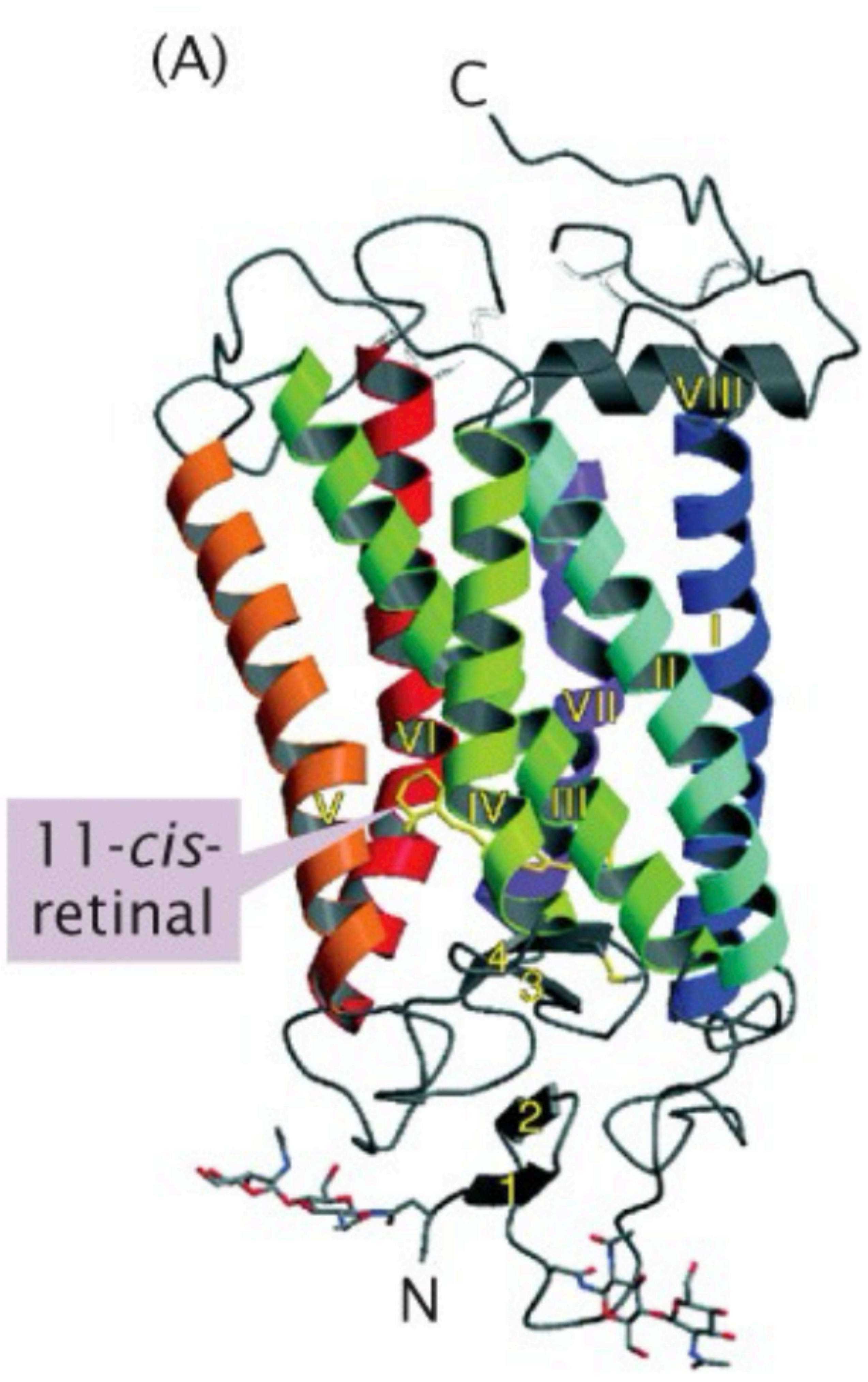
"Rod" cells do the work when light intensity is low (night vision!)

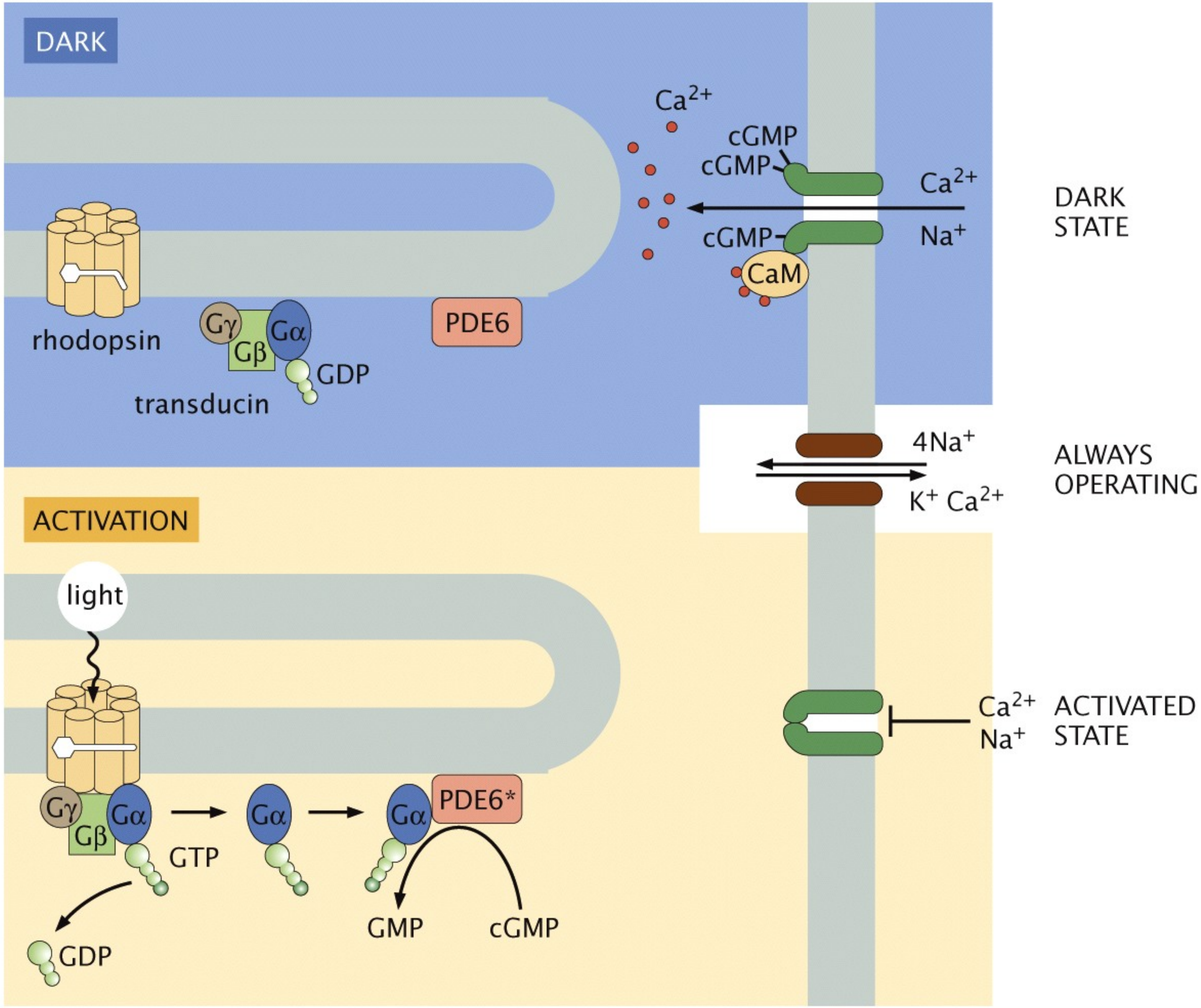
Cone cells do the work when light intensity is high

Rod cells have proteins call rhodopsin



Rhodopsin undergo conformational change when photon falls on it. Converts light energy to chemical potential

Huge number of rhodopsin molecules so that even a single photon is captured and NOT lost in the cell



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Conformational change of rhodopsin lead to a series of chemical reactions leading to ion-channel opening/closing and voltage difference

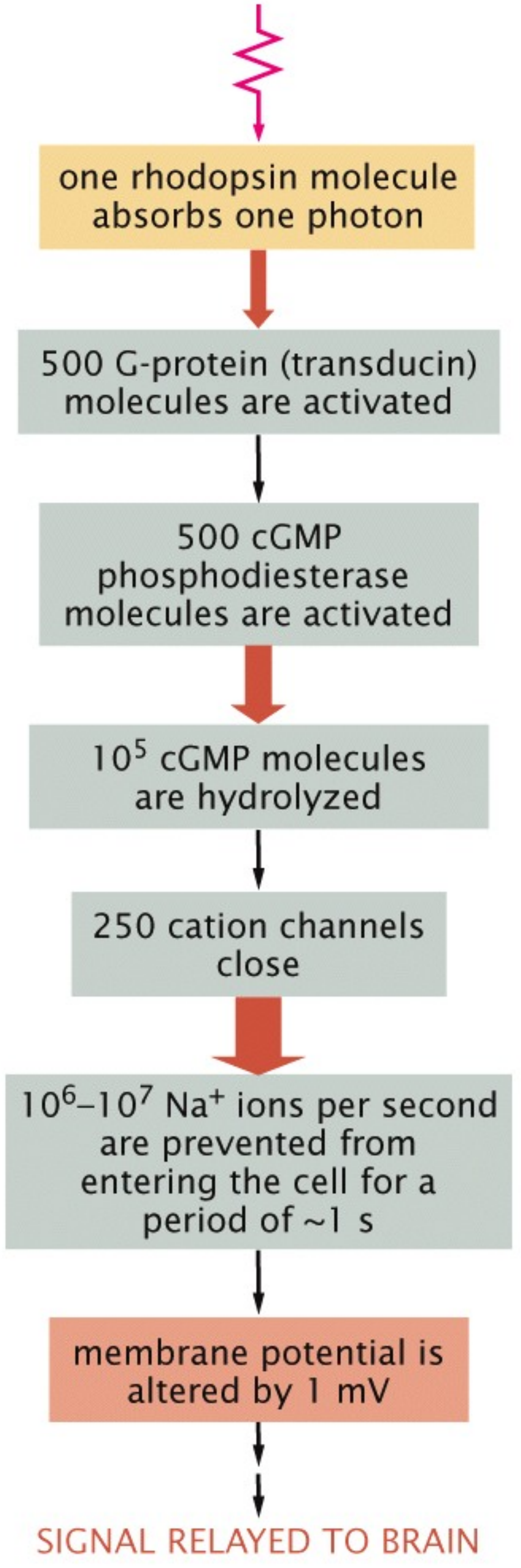
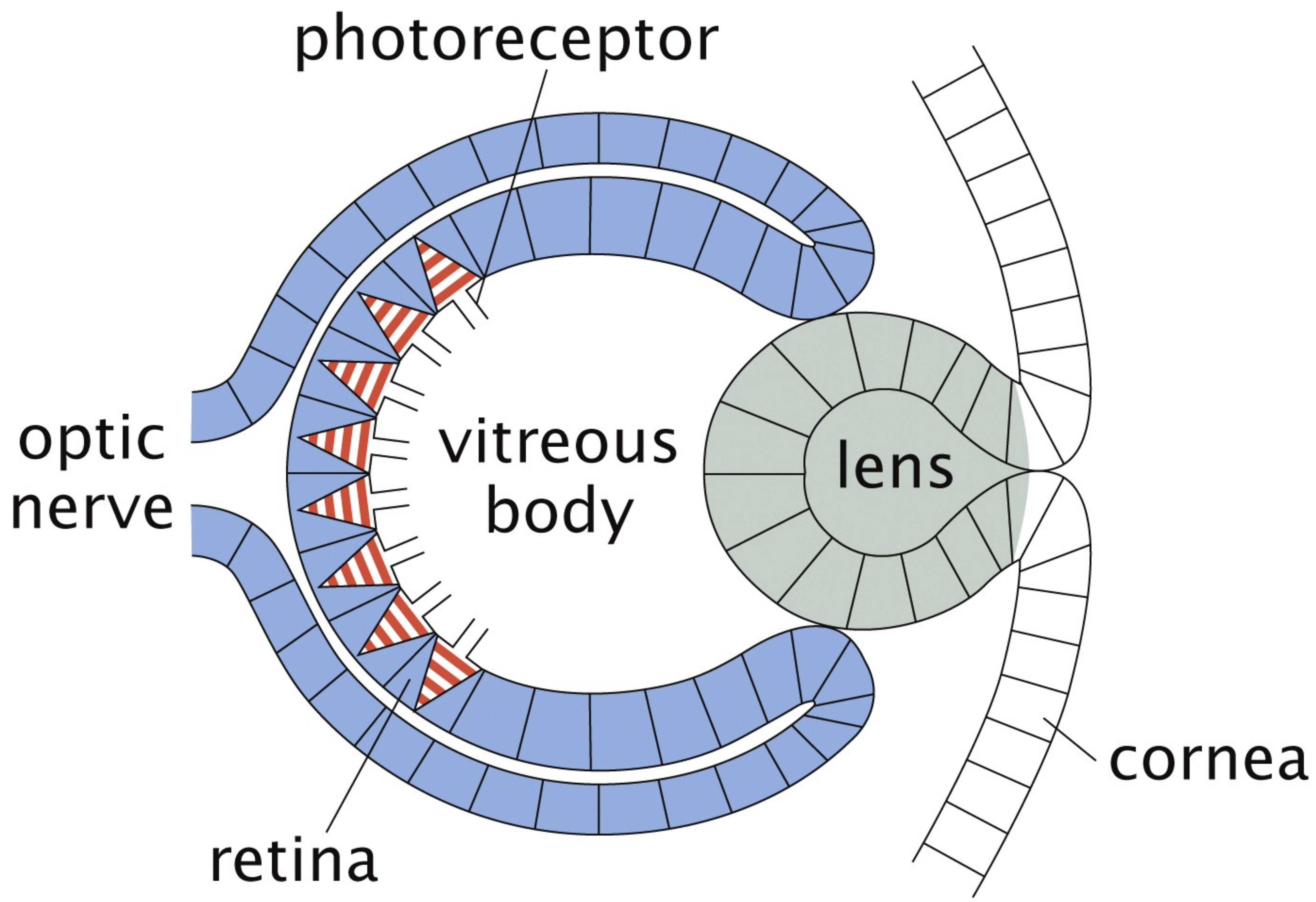


Figure 18.46b Physical Biology of the Cell, 2ed. (© Garland Science 2013)

The signal is amplified through an "amplifier" (chemical reactions.)

Brain detects the electrical signal



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Summary

- Research papers have the latest knowledge!
- Experiment to test whether eye can detect single photos
- Use of simple statistics ideas
- Biology of eye
- Rod cells
- Rhodopsin molecules and their confirmation changes