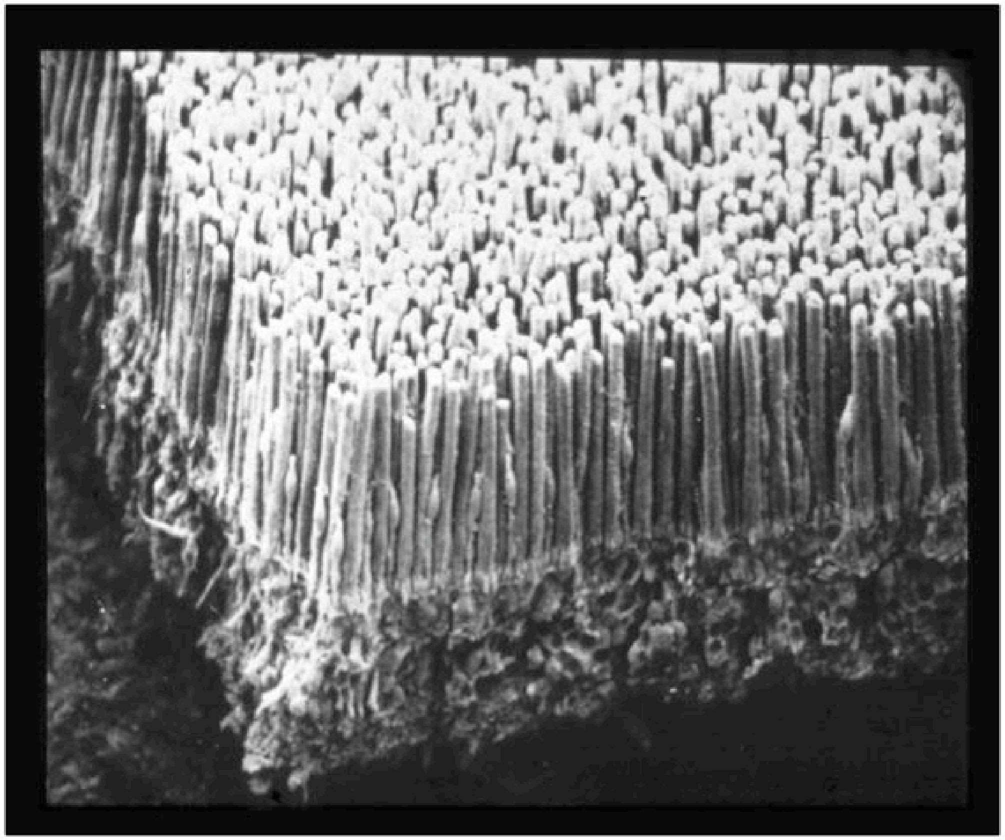
[redacted]

Photon detection near the absolute threshold of vision



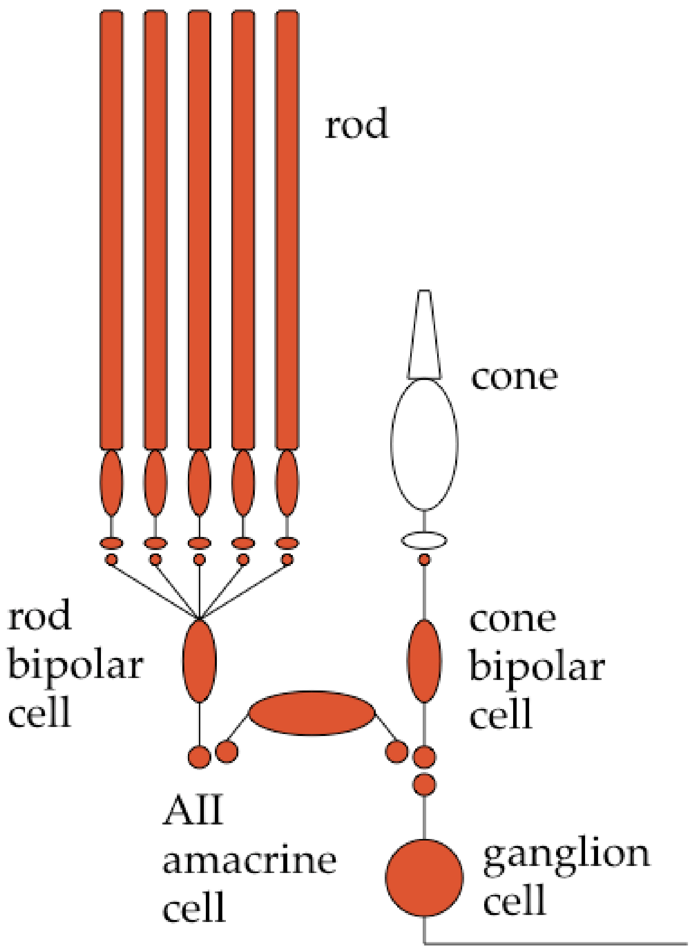
What constraints does behavioral sensitivity place on detection and processing in retina?

- what is absolute sensitivity of behavior?
- what are properties of noise limiting behavioral sensitivity?

What are properties of single photon responses in rod photoreceptors and how do they relate to behavior?

How are signals resulting from absorption of a few photons maintained through retina?

Photon detection near the absolute threshold of vision



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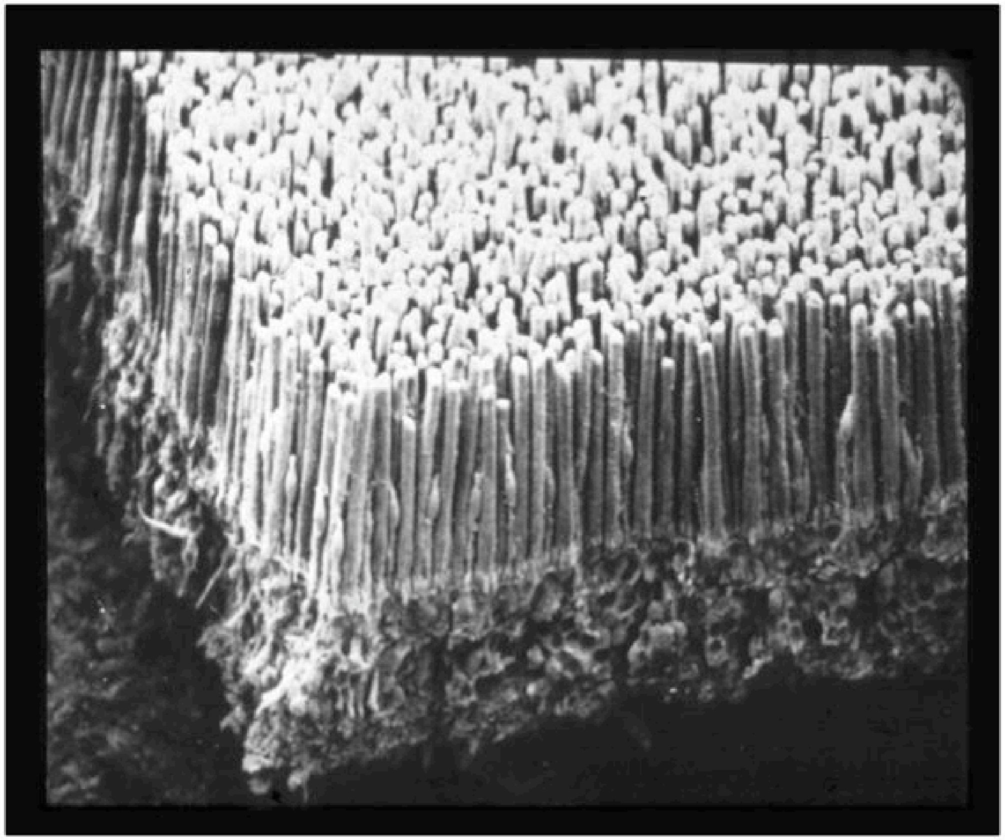

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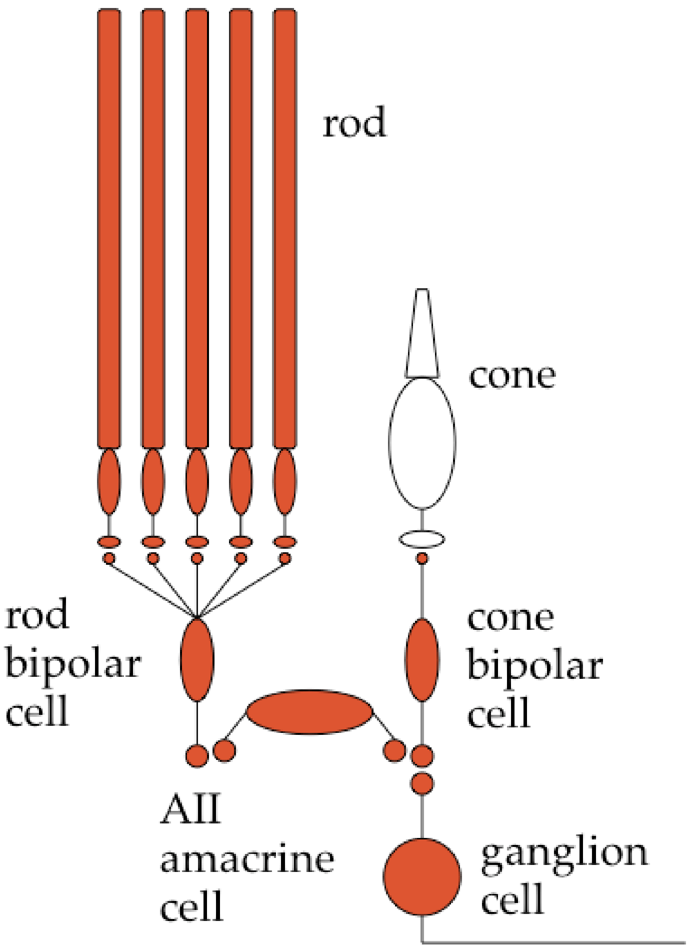
Detecting single photons



What limits visual sensitivity?

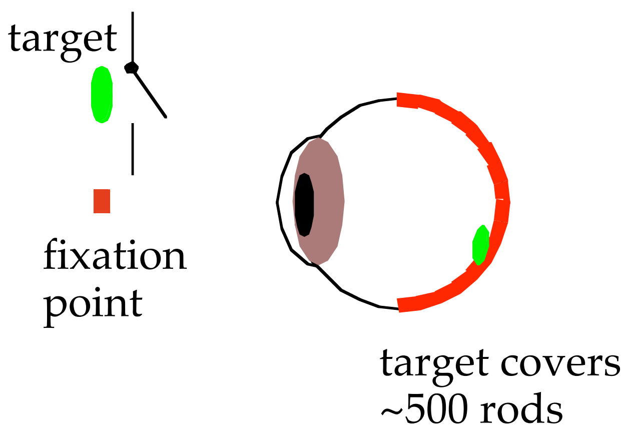
<u>Main idea:</u>
Behavioral sensitivity is limited by Poisson variability in the number of photons absorbed and a source of noise ("dark light") that arises in the rod photoreceptors.

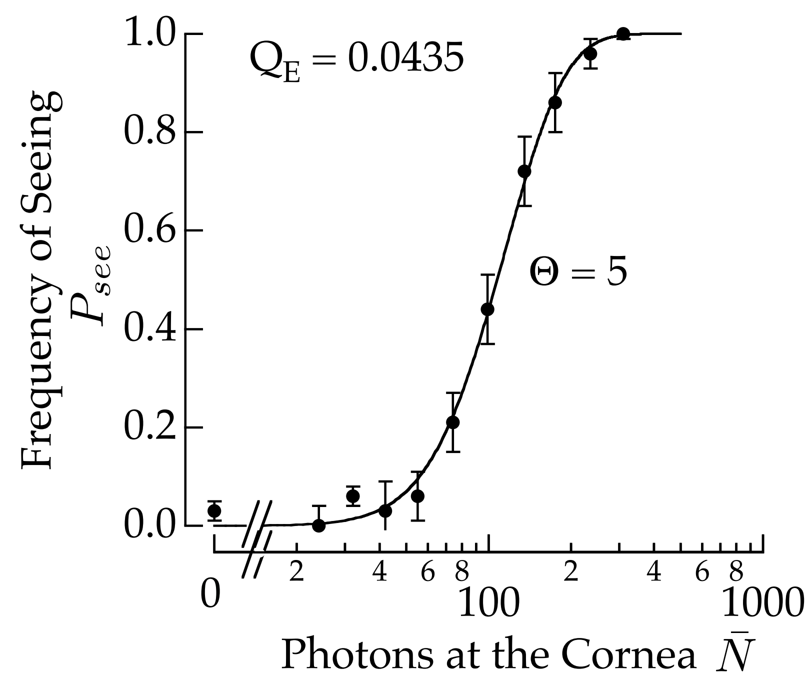
This noise source is associated with the spontaneous activation of rhodopsin.

If true, this implies that the rest of the retinal circuitry and the brain efficiently and effectively noiselessly processes rod signals.

Frequency of seeing experiments

Hecht, Shlaer and Pirenne, 1942
Teich *et al*. 1982





Poisson statistics

$$P(n) = \frac{e^{-\mu}\mu^n}{n!}$$

n = number of counts
μ = mean counts

assume a threshold Θ

→

sum over distributions
define a quantum efficiency Q_E

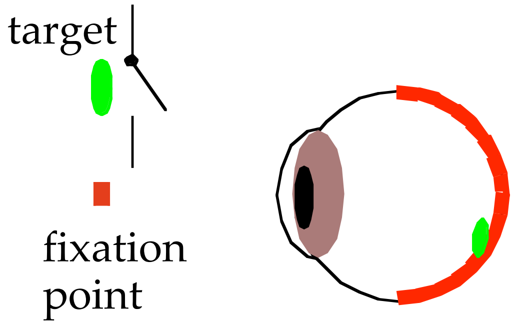
fit data

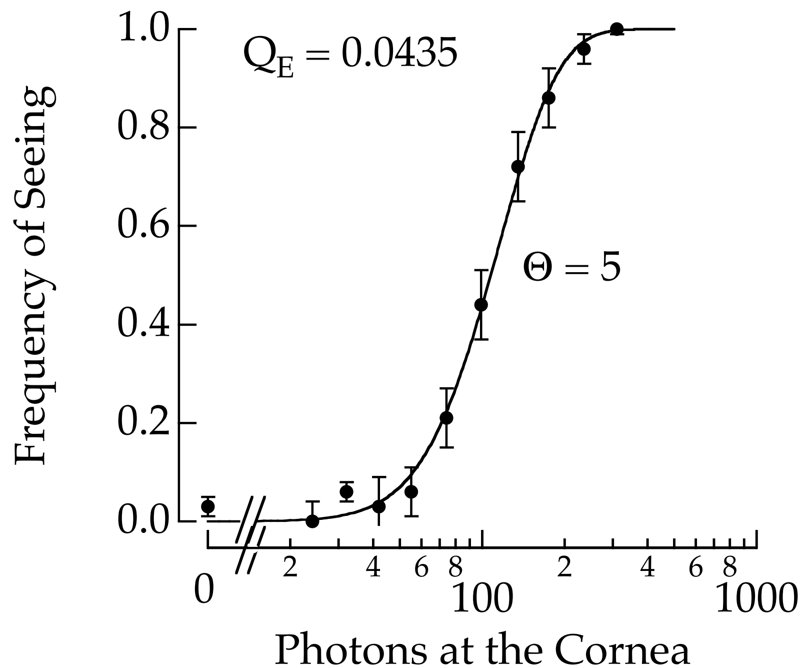
$$P_{see} = \sum_{n \geq \Theta}^{\infty} \frac{\exp(-Q_E\bar{N})(Q_E\bar{N})^n}{n!}.$$

P_{see} = frequency of seeing
N = photons # at cornea
n = number of absorbed photons

Frequency of seeing experiments

Hecht, Shlaer and Pirenne, 1942
Teich *et al*. 1982

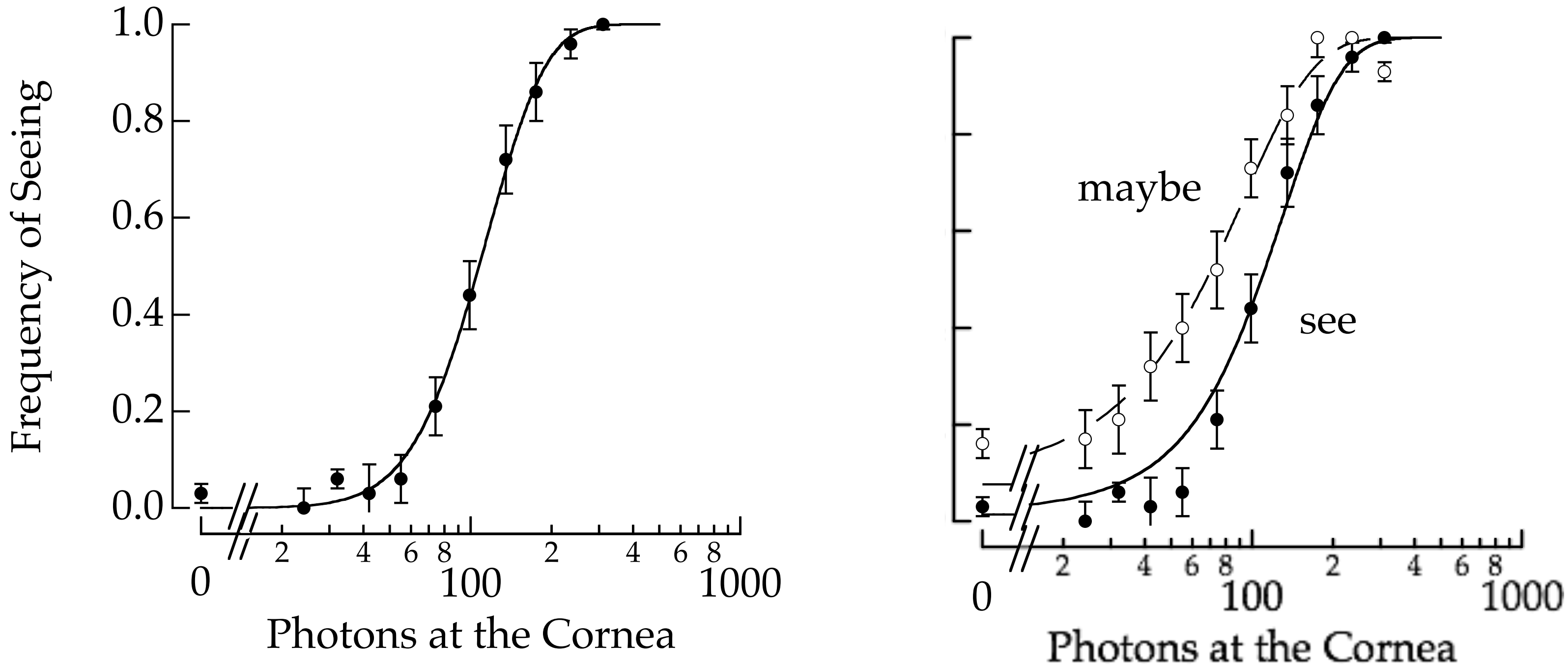




Conclusions:
1. It is unlikely that a single rod is receiving more than one photon.
2. Vision may be limited by physical nature of the stimulus rather than biological noise.

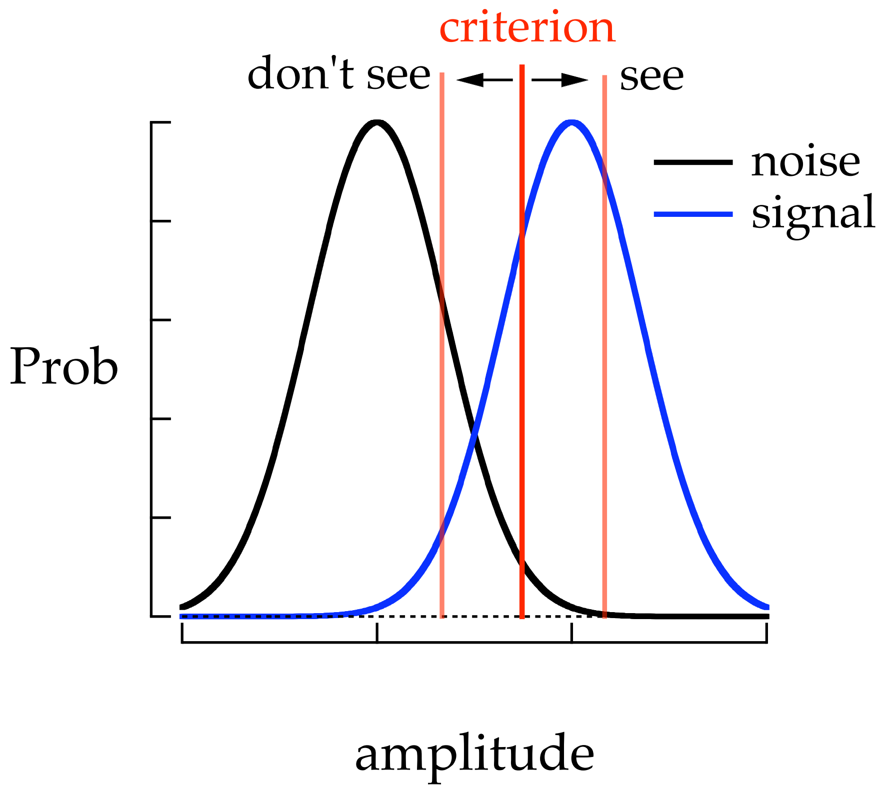
Problems:
1. No way to account for false positive reports by the observer
2. Very low quantum efficiency.

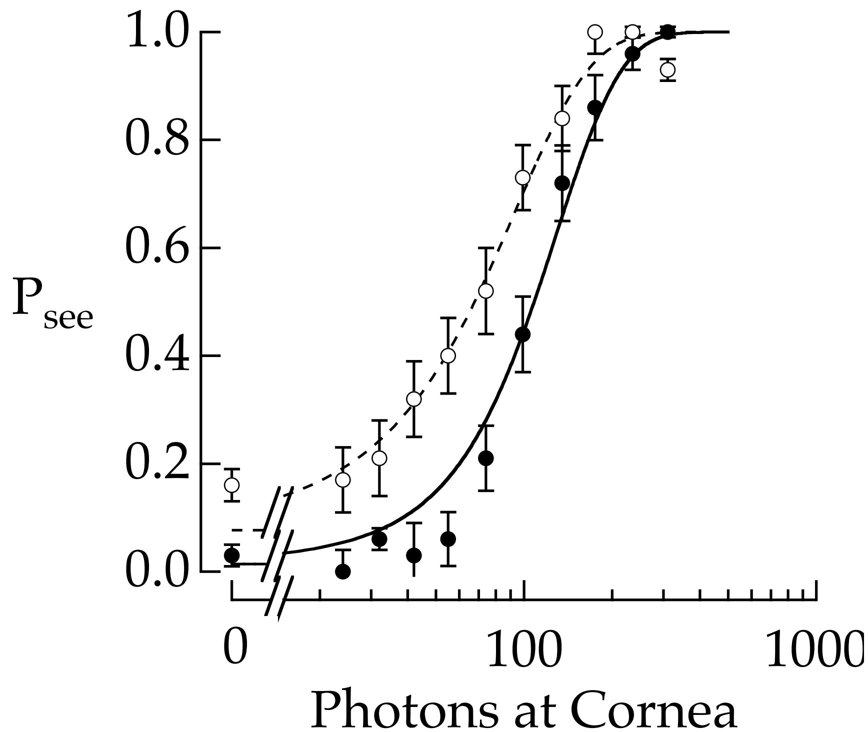
Subjects can demonstrate a lower threshold if allowed more false positive responses



THRESHOLD TRADES FOR FALSE POSITIVES

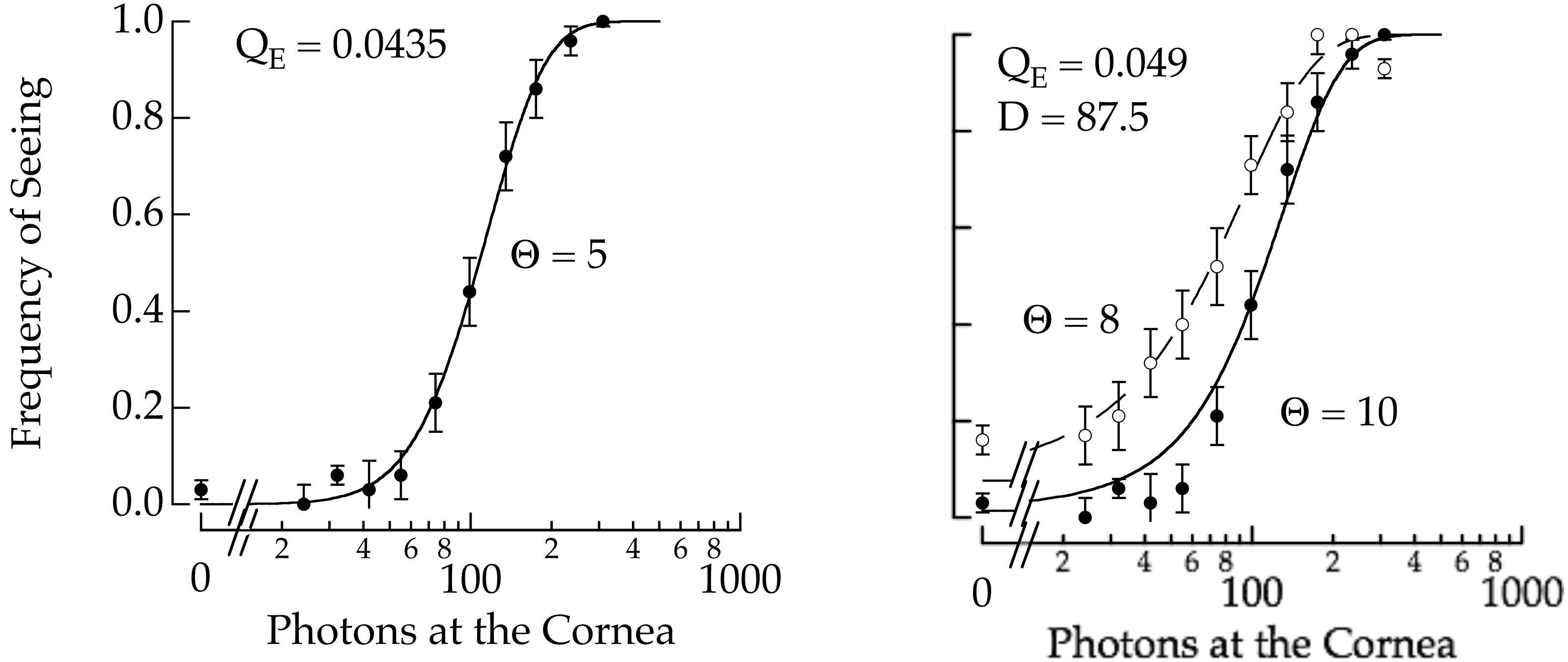
(Barlow, 1956; Teich et al., 1982)





information from small # of photons available, but accessing it produces errors due to intrinsic noise

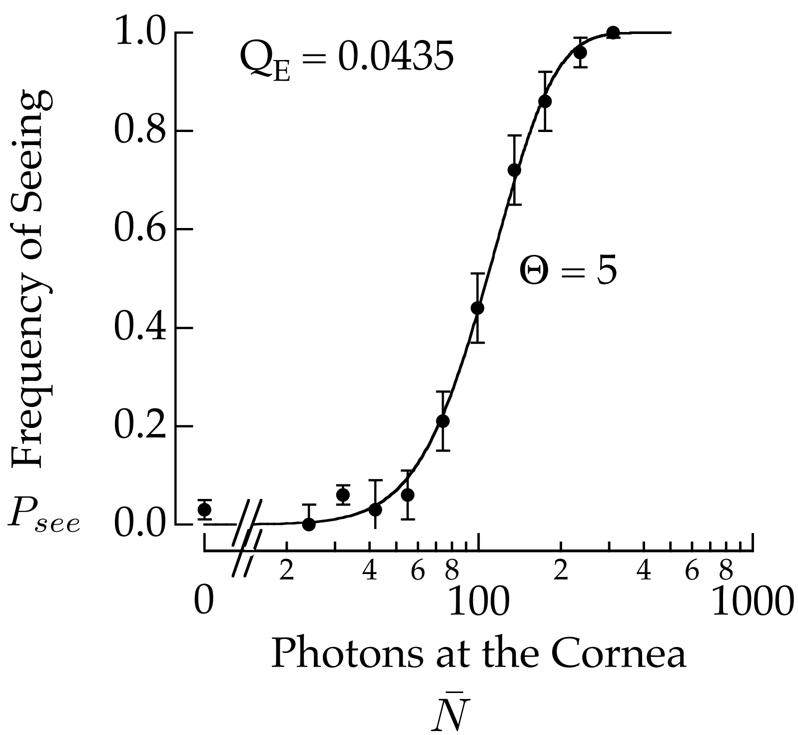
A source of photon-like noise ("dark-light") can account for false positives

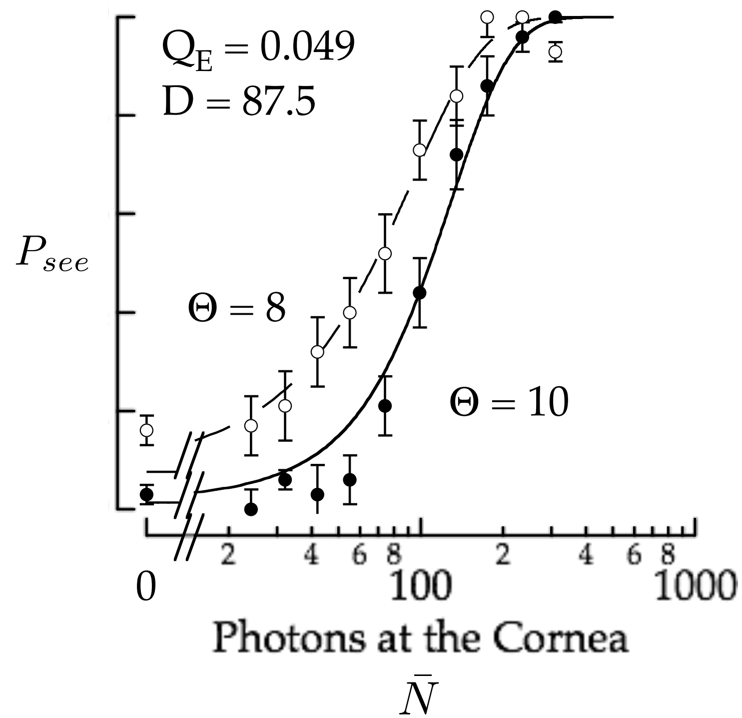


$$P_{see} = \sum_{n \geq \Theta}^{\infty} \frac{\exp(-Q_E \bar{N})(Q_E \bar{N})^n}{n!}.$$

$$P_{see} = \sum_{n \geq \Theta}^{\infty} \frac{\exp(-Q_E(\bar{N} + D))(Q_E(\bar{N} + D))^n}{n!}.$$

A source of additive photon-like noise can account for false positives

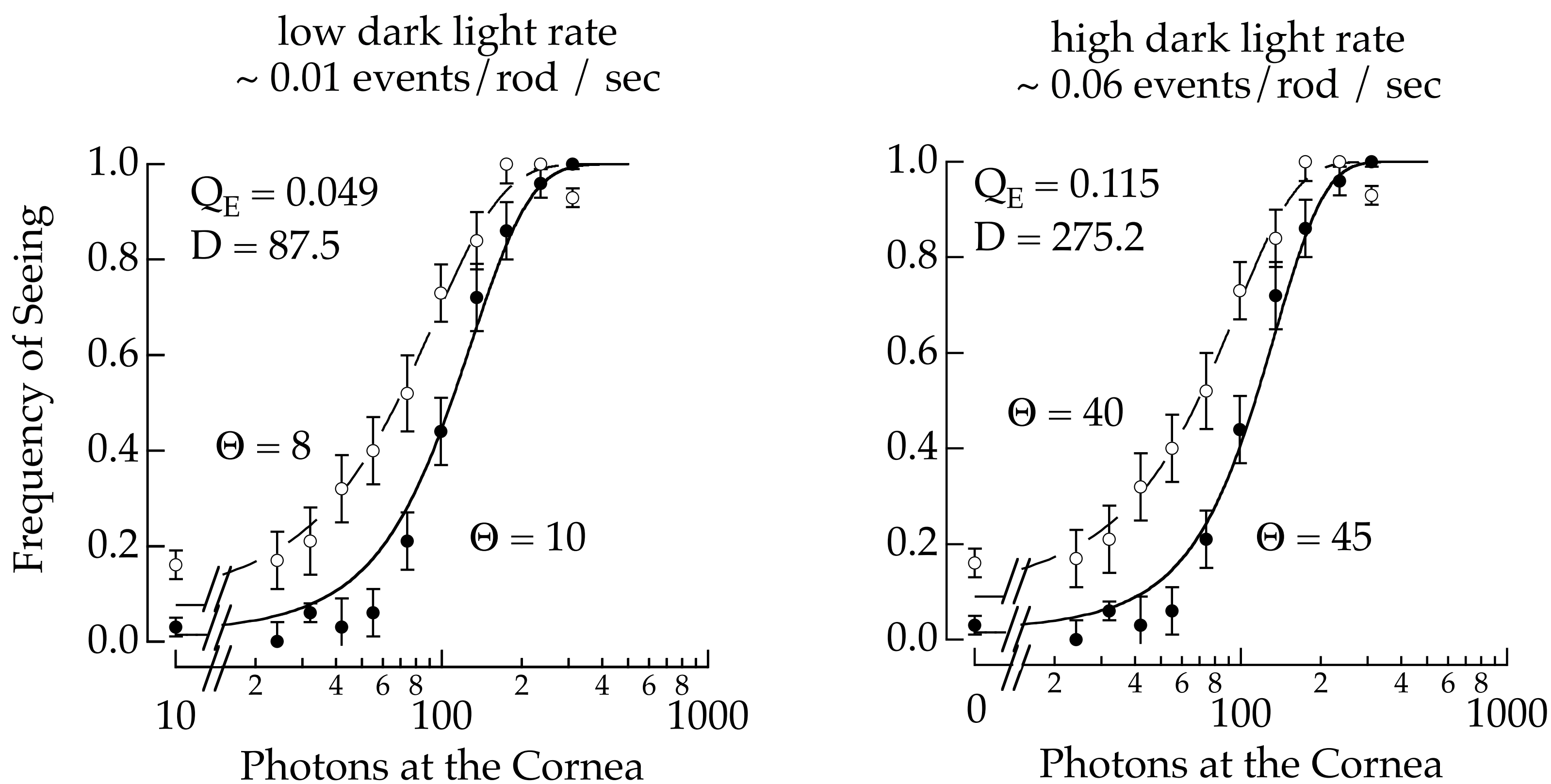




1) Dark light (D) can be converted into an equivalent rate of noise events in the rods $d = 0.01$ events per rod per second (range *0.005 - 0.03*).
2) There exists a source of photon-like noise ("thermals") in the rods that occurs at a rate ~ 0.01 (between *0.004 - 0.02)* events per rod per second.

We have accounted for the false positive responses, but what about the very low quantum efficiency?

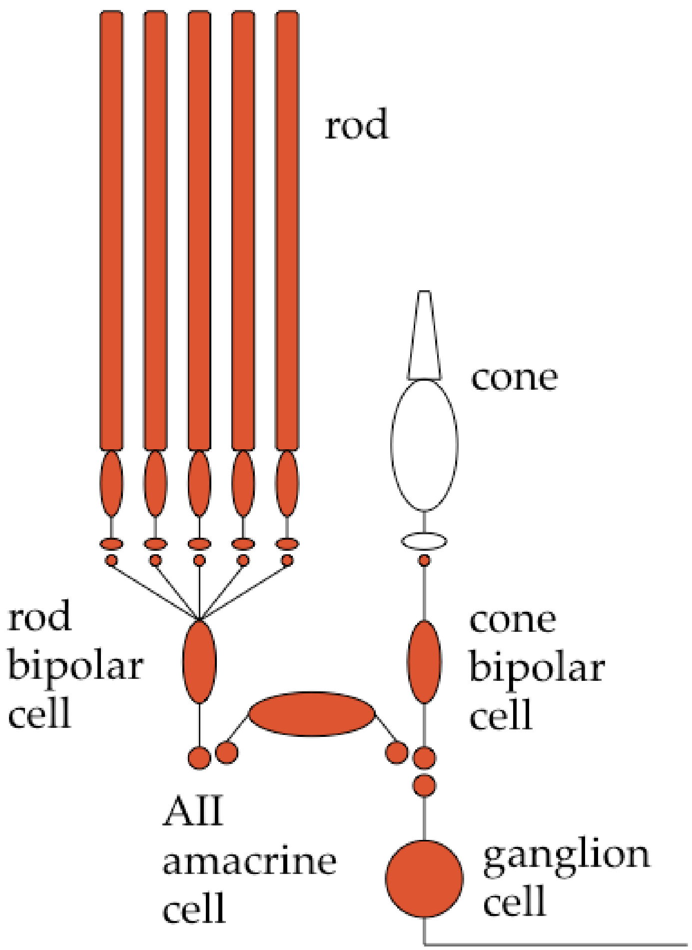
Is visual sensitivity really limited by the thermal activation of rhodopsin?



- With a low threshold, the thermals can explain all the noise limiting visual performance.

- With a high quantum efficiency, the thermals **cannot** explain the noise limiting visual performance.

Where does this ambiguity leave us?



Possibility 1: Rod noise limited vision

A) no additional noise

B) efficient processing

Possibility 2: noisy visual processing

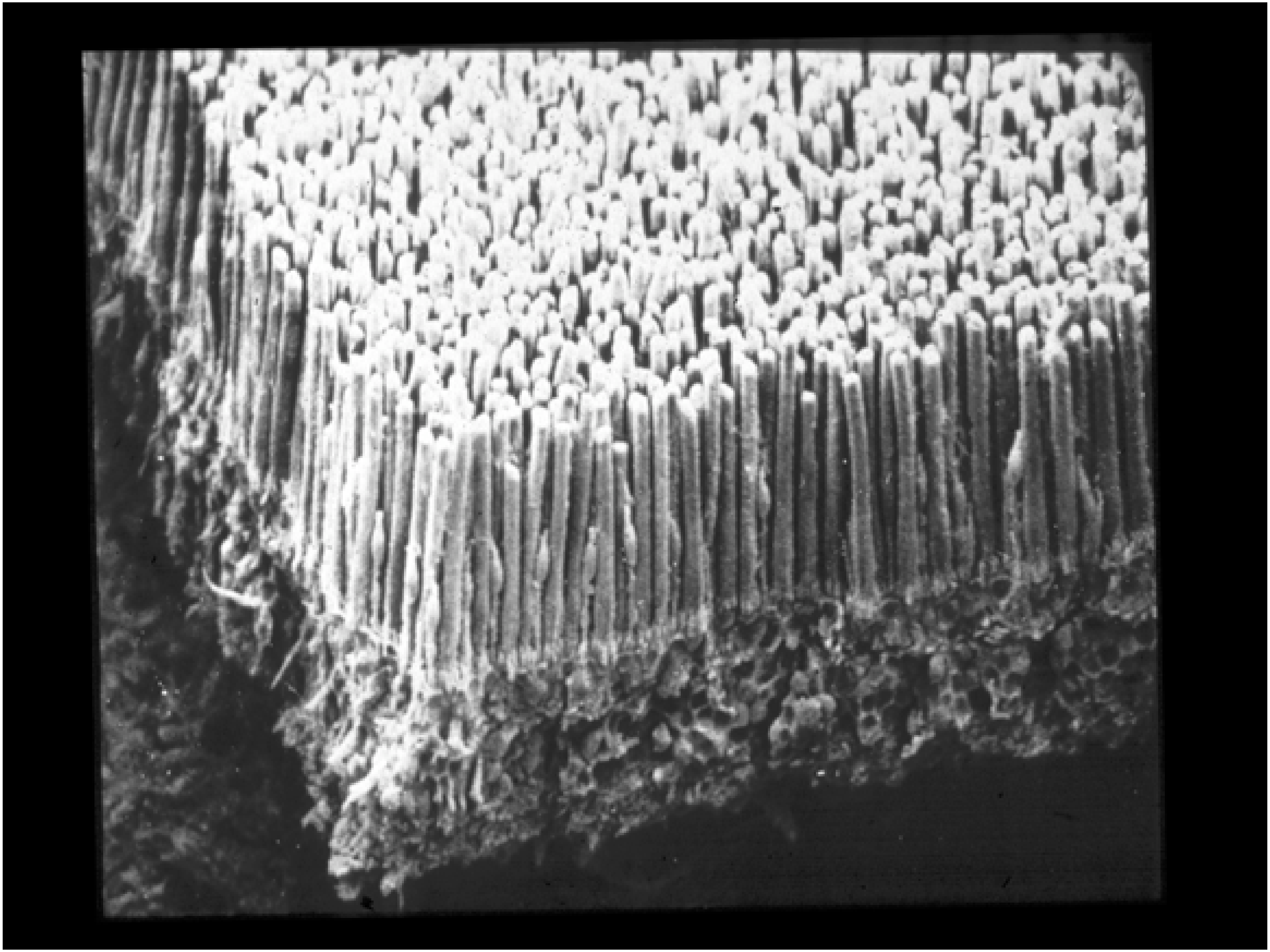
A) synaptic noise?

B) noise in spike generation?

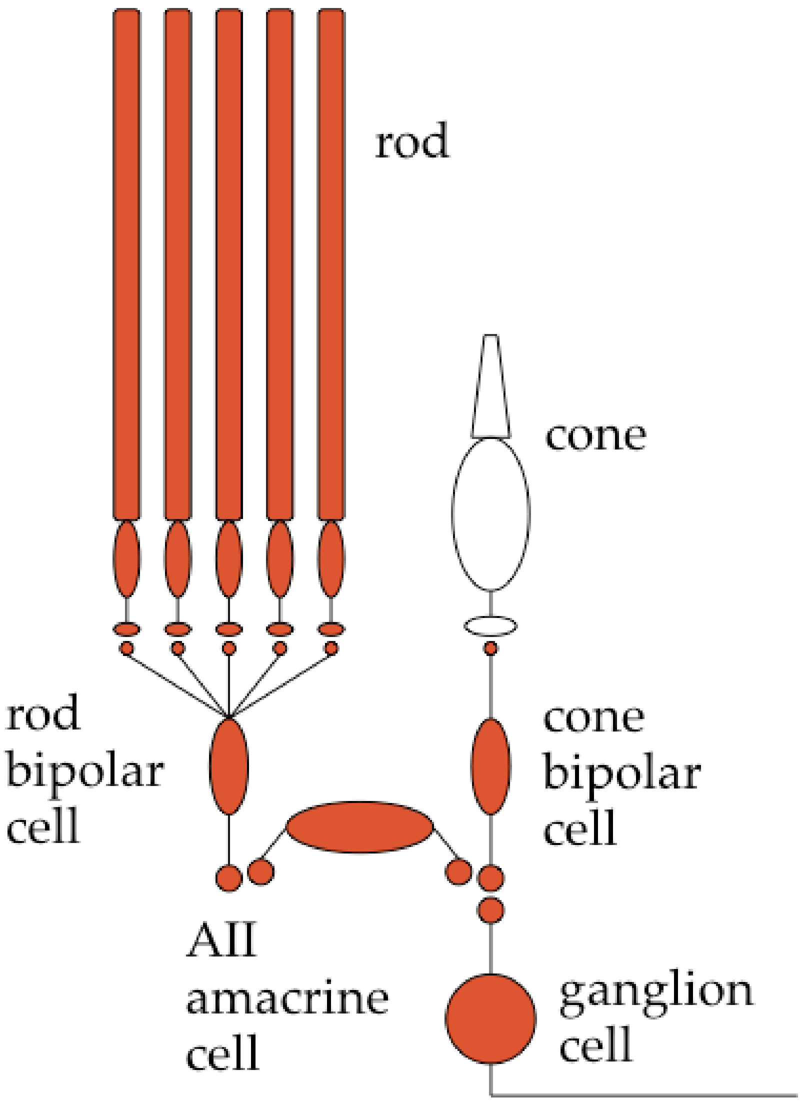
Retinal Physiology

"Are we looking for the additional noise or the mechanisms that are responsible for efficient processing?"

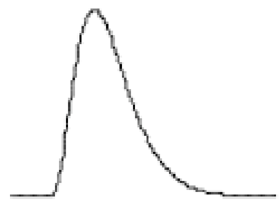
What have we learned from the physiology?



Detecting a sparse signal across many noisy detectors



- phototransduction:
  - single photons reliably transduced



- synaptic transmission:
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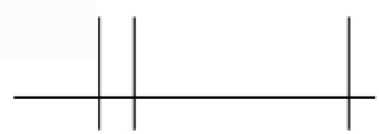
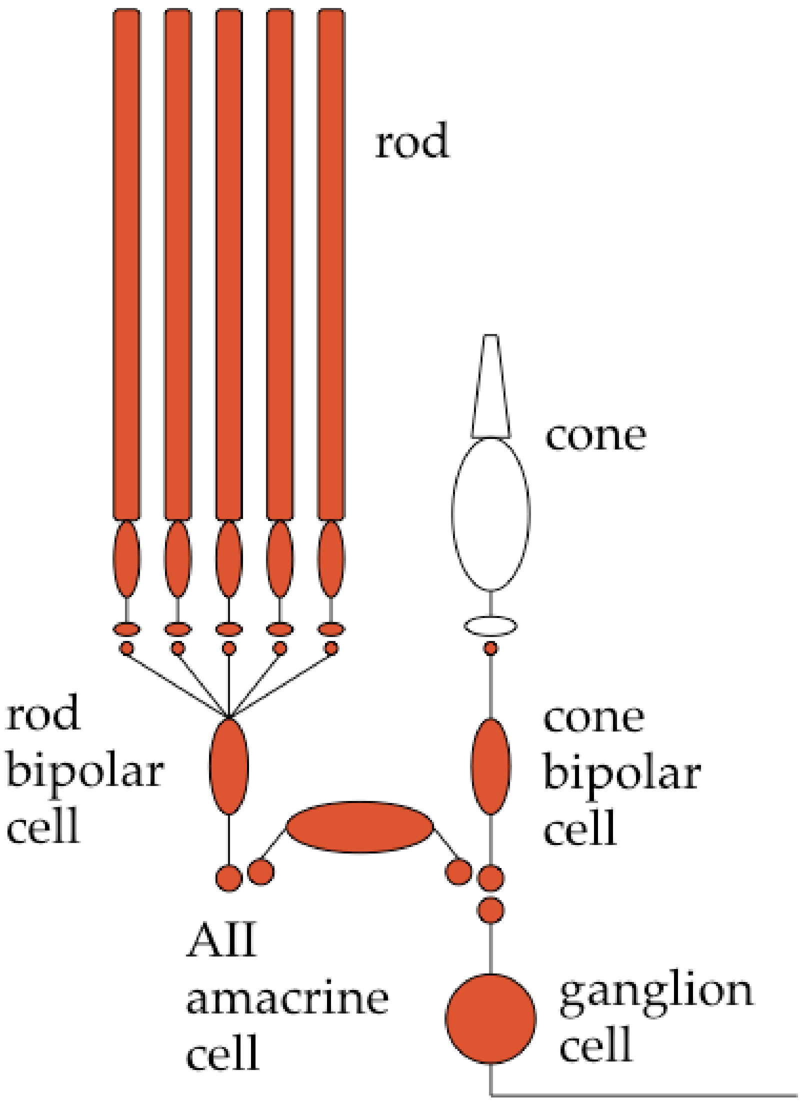


Rod Phototransduction



Rods generate "large" responses to the absorption of a single photon

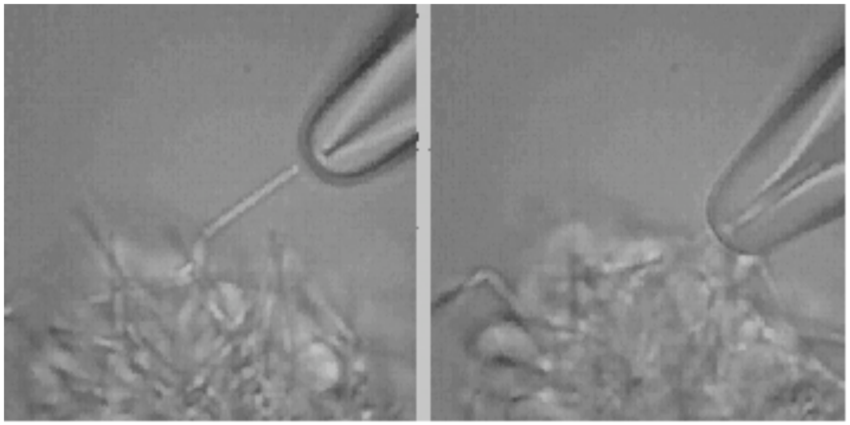
Rods also generate three primary types of noise:

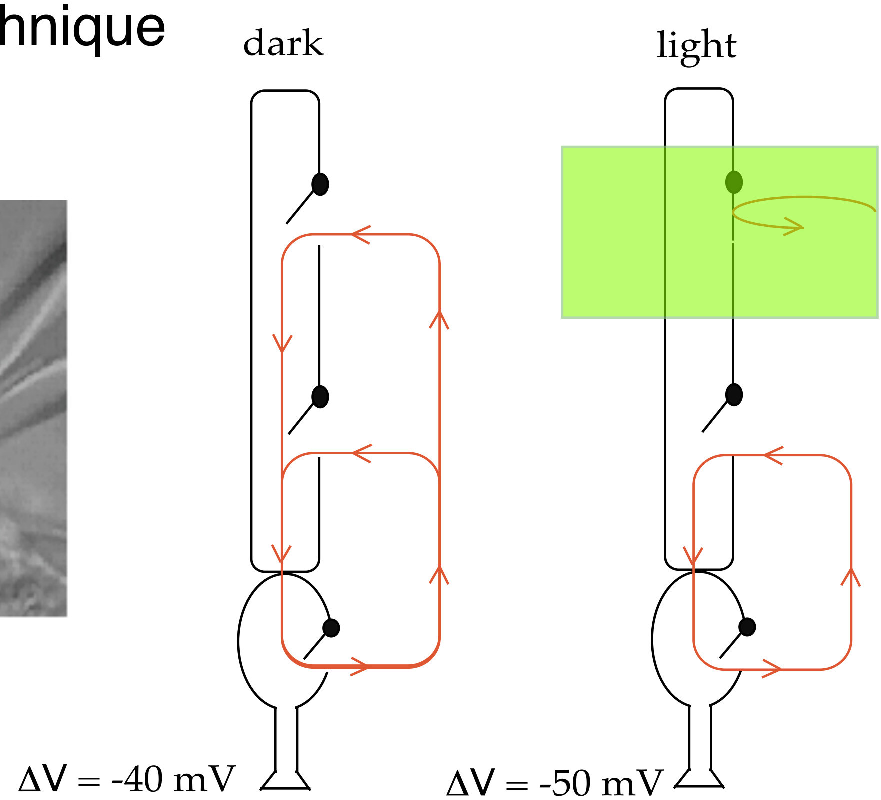
1.) continuous noise

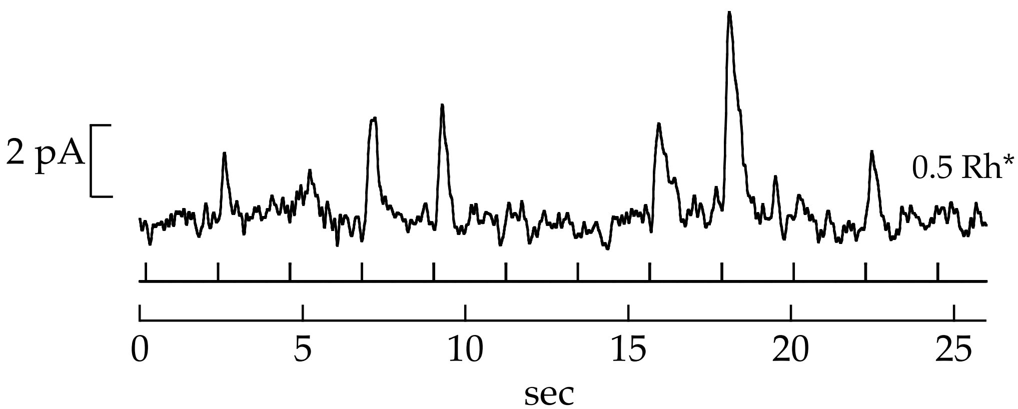
2.) spontaneous activation of rhodopsin (thermals)

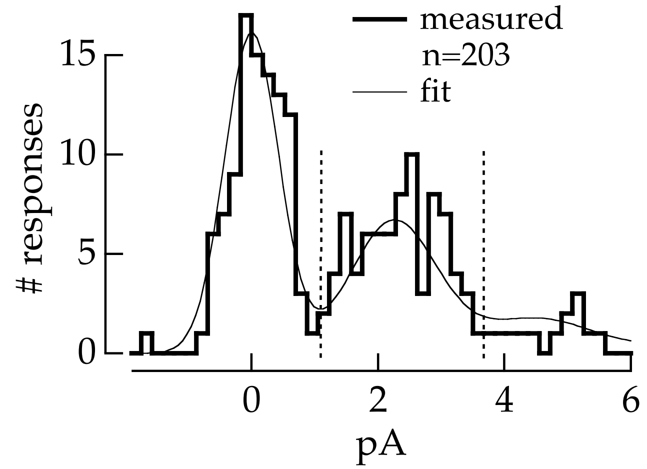
3.) fluctuations in the single photon response

Suction electrode recording technique

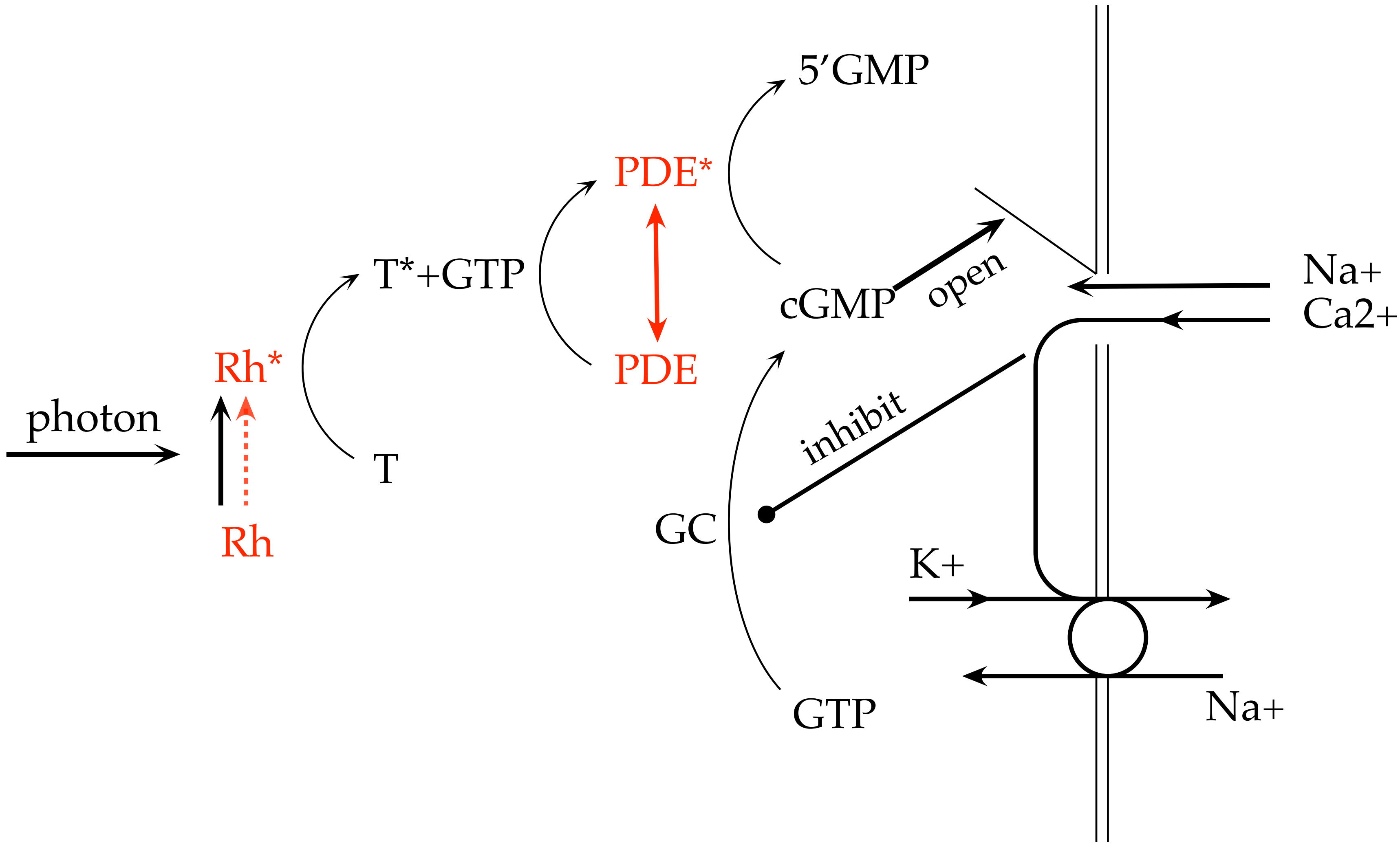




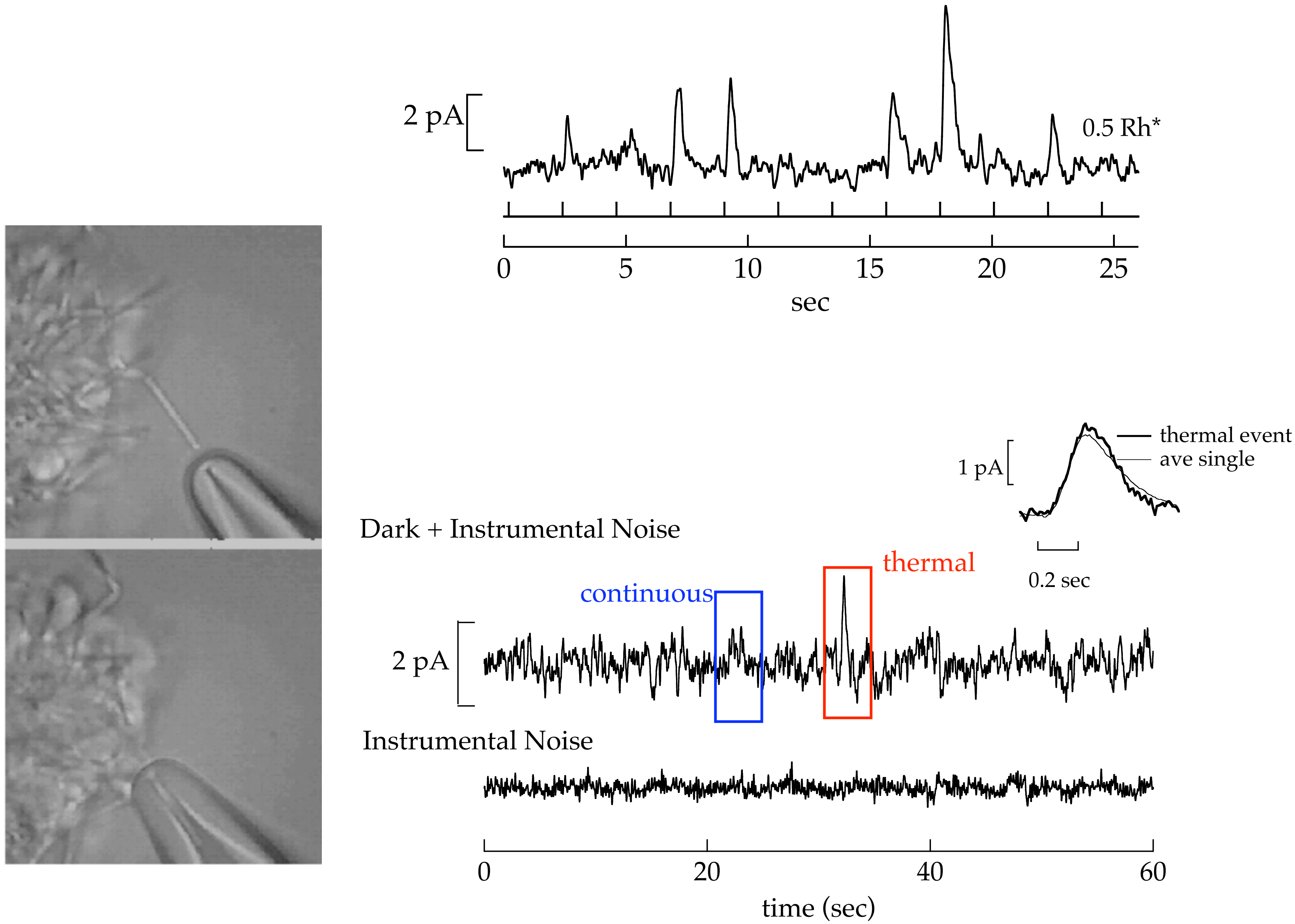




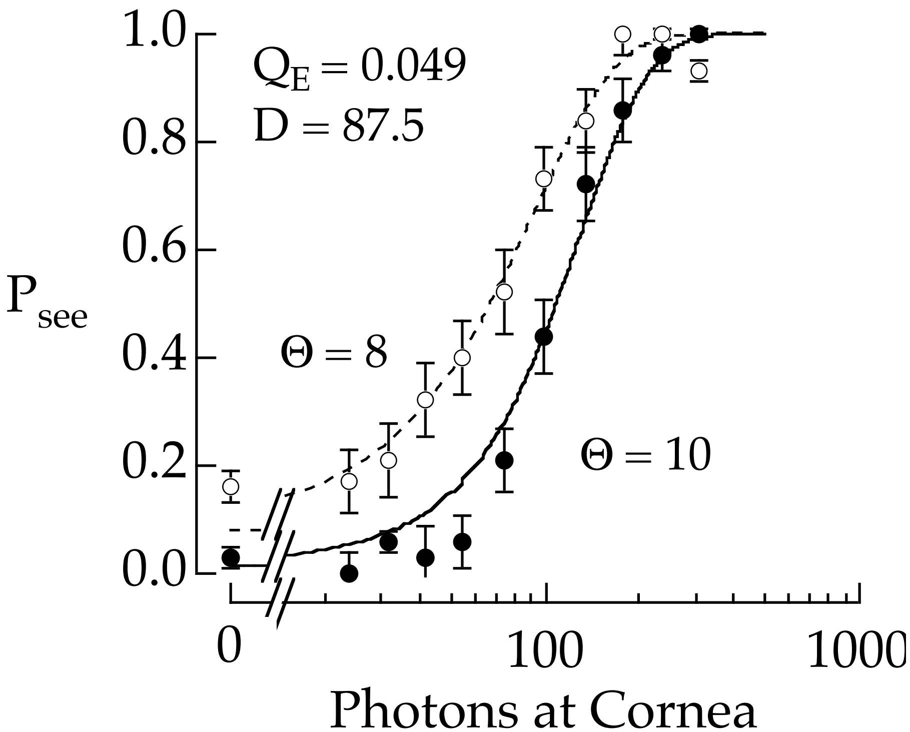
Rod phototransduction



Primate rod photoreceptor signal and noise



BEHAVIORAL “DARK LIGHT” CLOSE TO THERMAL RATE IN RODS



BEHAVIOR:

dark noise equivalent to ~0.01-0.03 photon-like noise events per sec per rod

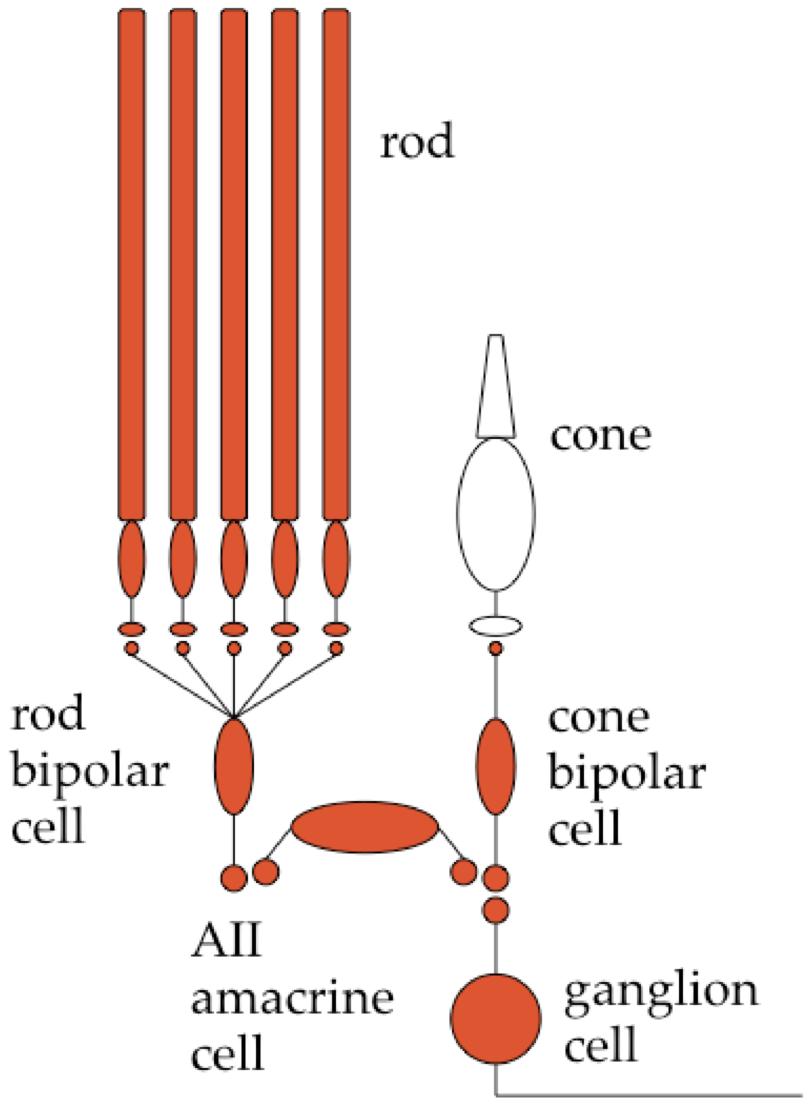
DISCRETE ROD NOISE:

event rate ~0.005-0.01 per sec

TO THINK ABOUT:

what happened to continuous noise?

Detecting a sparse signal across many noisy detectors



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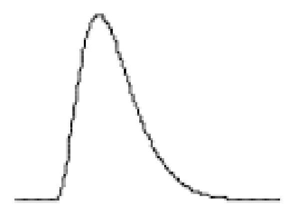

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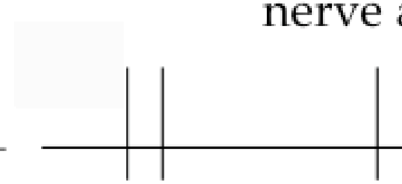
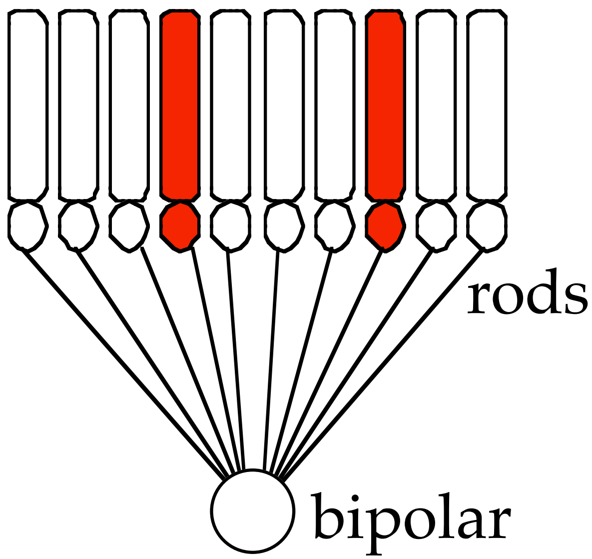


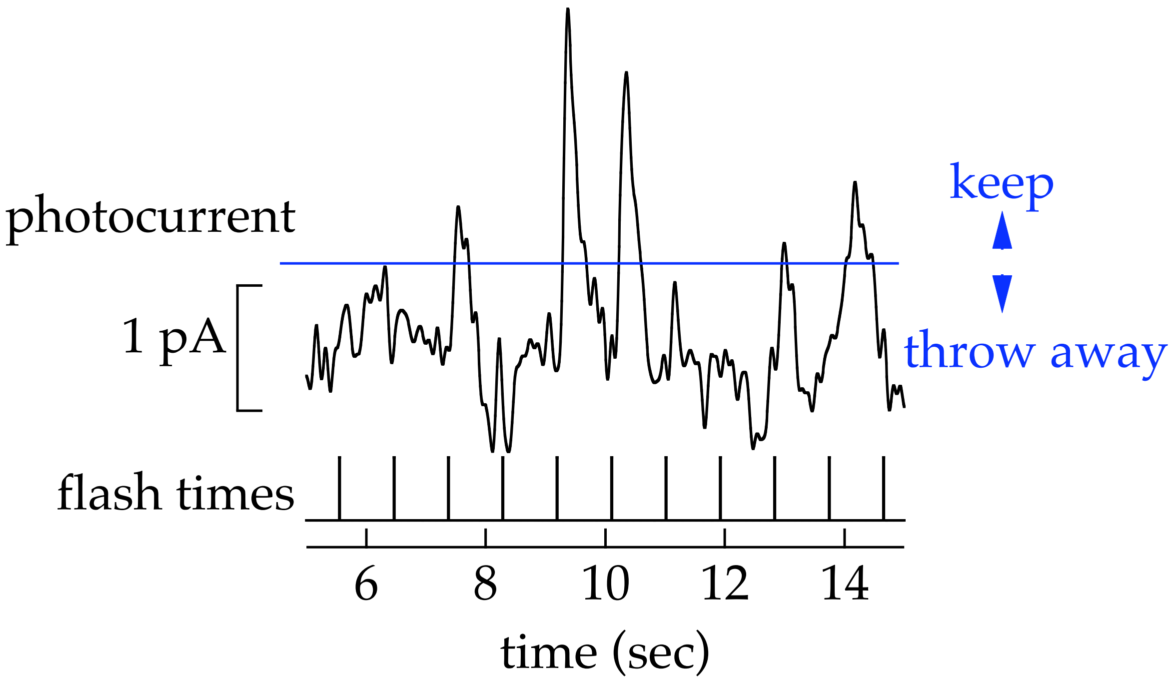
CONVERGENCE AND SPARSE SIGNALING
IN MAMMALIAN RETINA



- At visual threshold, photons caught by a small fraction of rods contribute to each independent visual image

- Sensitivity can be substantially increased if signals from rods absorbing photons can be retained and others discarded - e.g. by thresholding

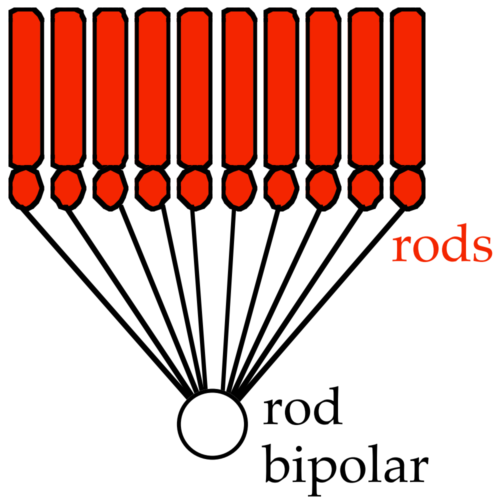
SEPARATION OF ROD SIGNAL AND NOISE BY THRESHOLDING NONLINEARITY

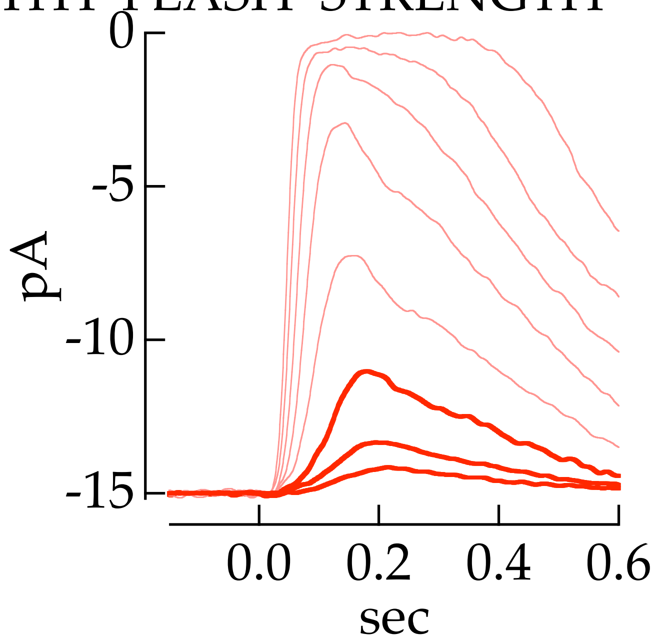


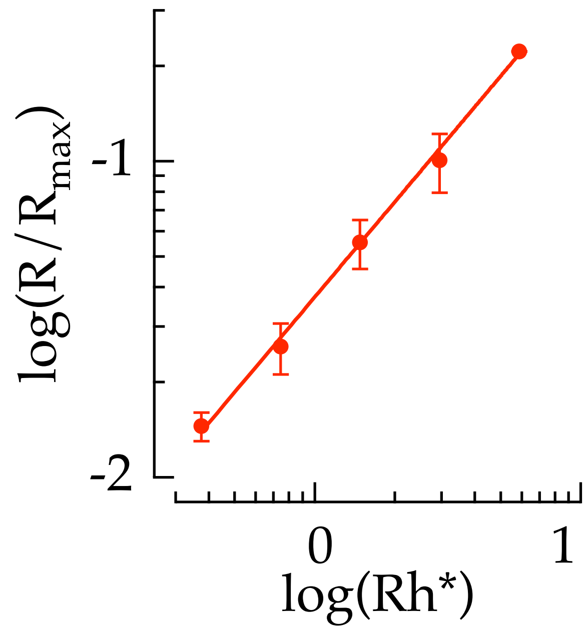
Does something like this happen in the retina?

Let's look at transmission between rods and bipolar cells to find out.

DIM FLASH RESPONSES OF RODS GROW LINEARLY WITH FLASH STRENGTH

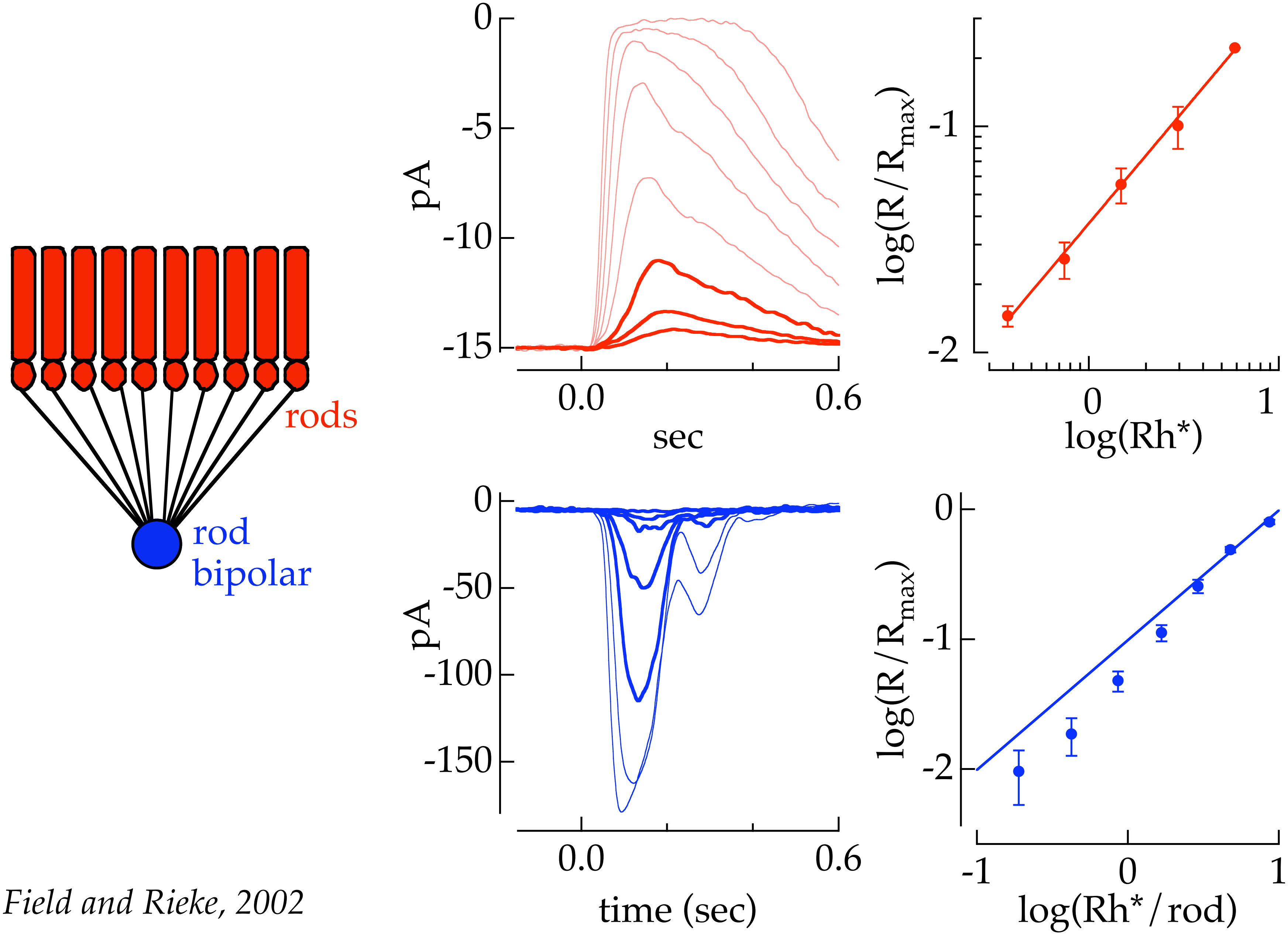




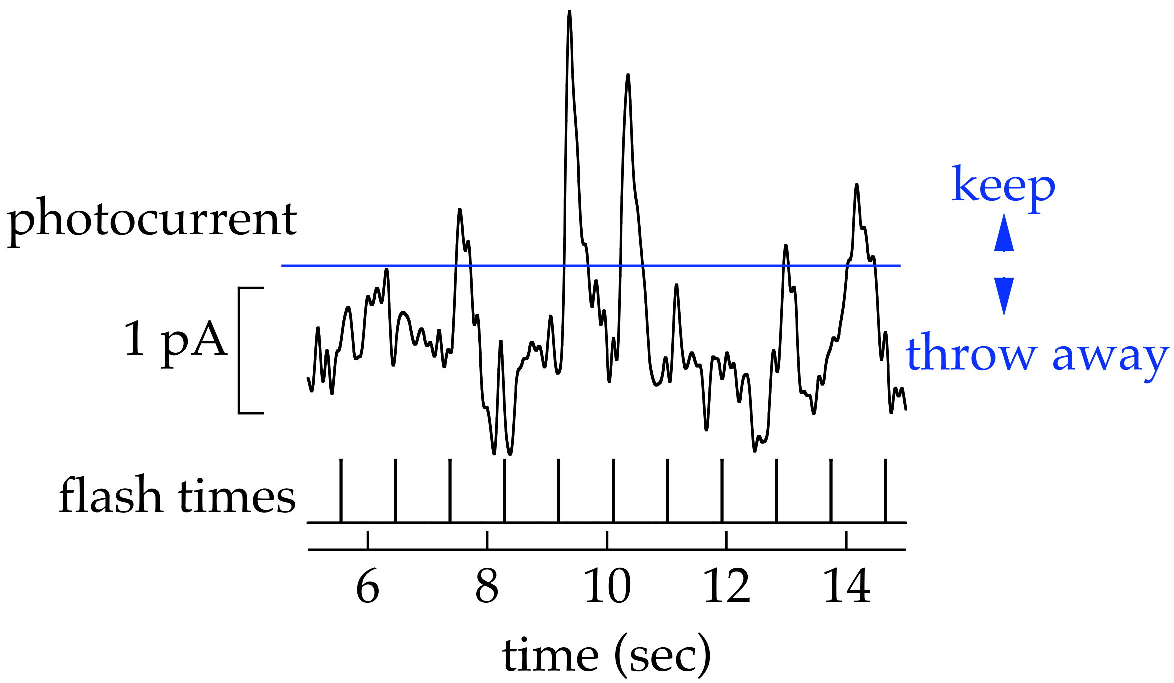


Field and Rieke, 2002

RESPONSES OF ROD BIPOLARS BUT NOT RODS GROW SUPRALINEARLY WITH FLASH STRENGTH

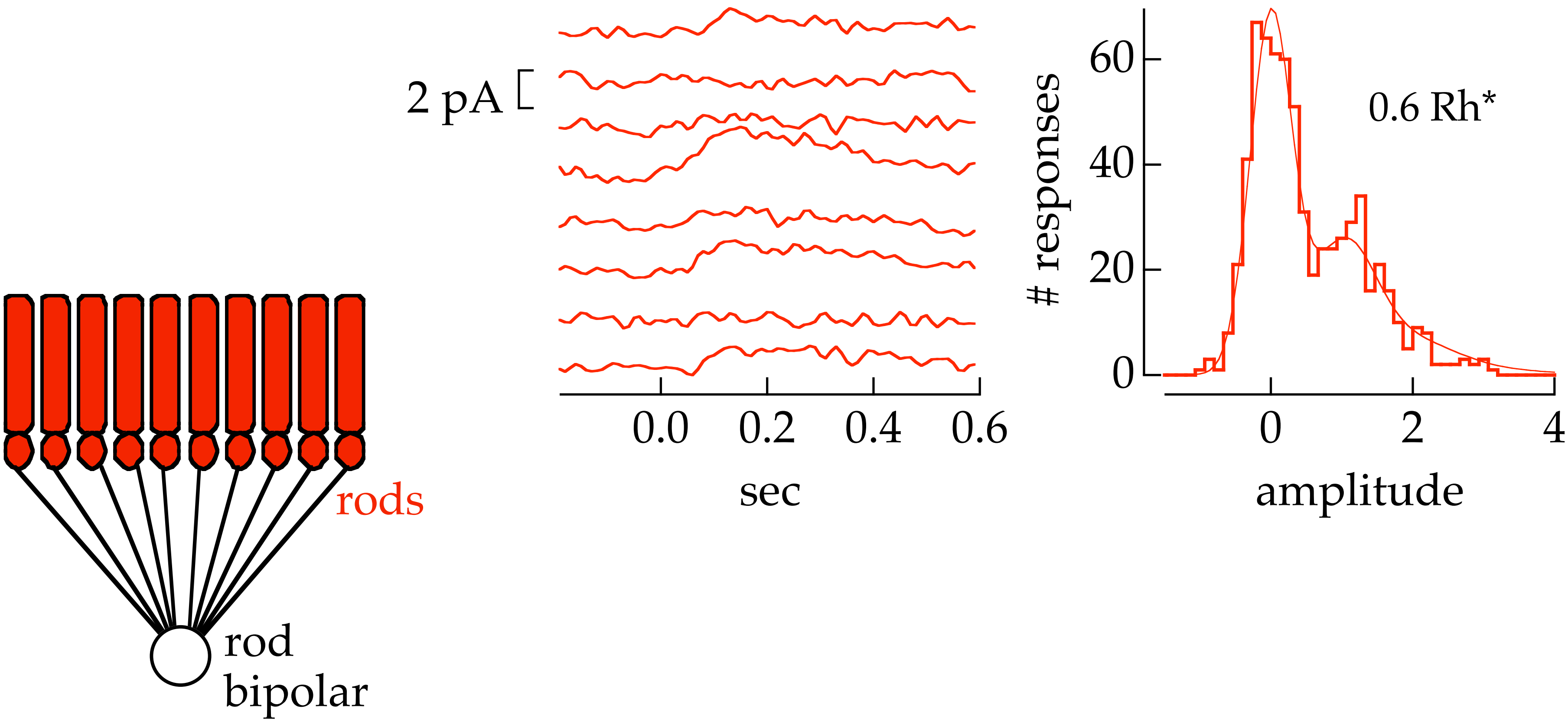


Field and Rieke, 2002

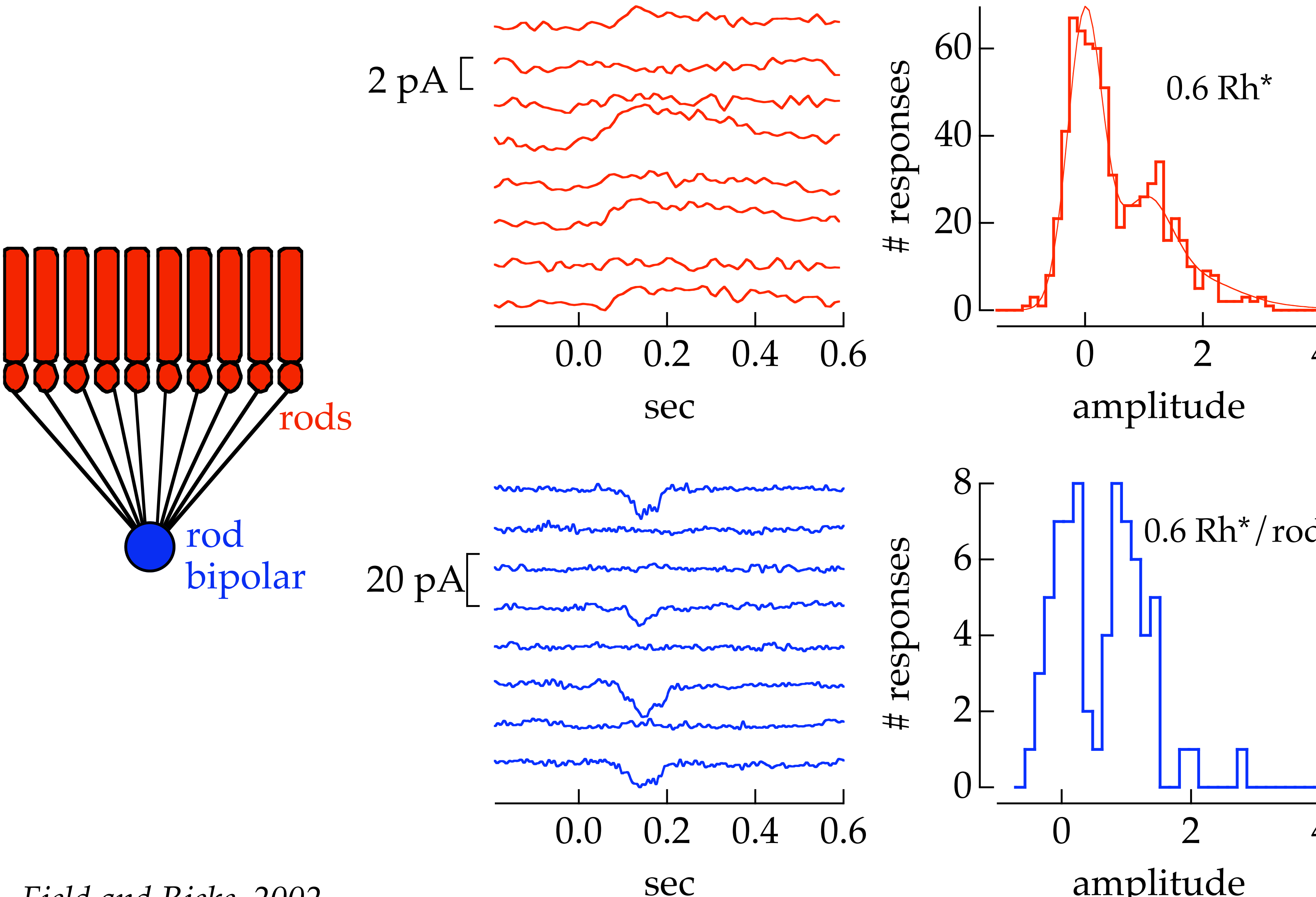


Does rod-rod bipolar signal transfer separate rod signal and noise?

MOUSE ROD SINGLE PHOTON RESPONSES ARE PARTIALLY OBSCURED BY NOISE

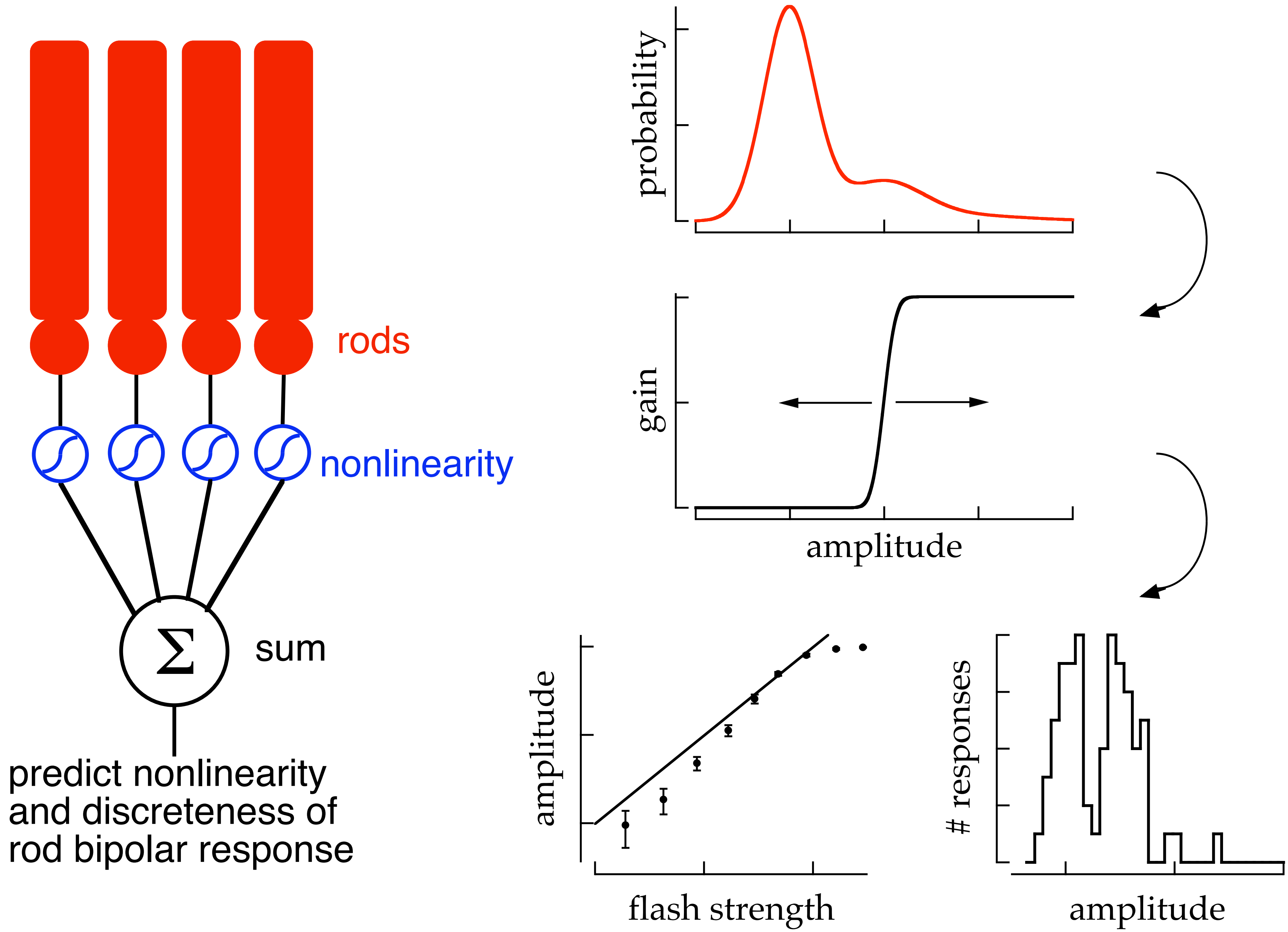


ROD BIPOLARS GENERATE DISCRETE RESPONSES TO DIM FLASHES

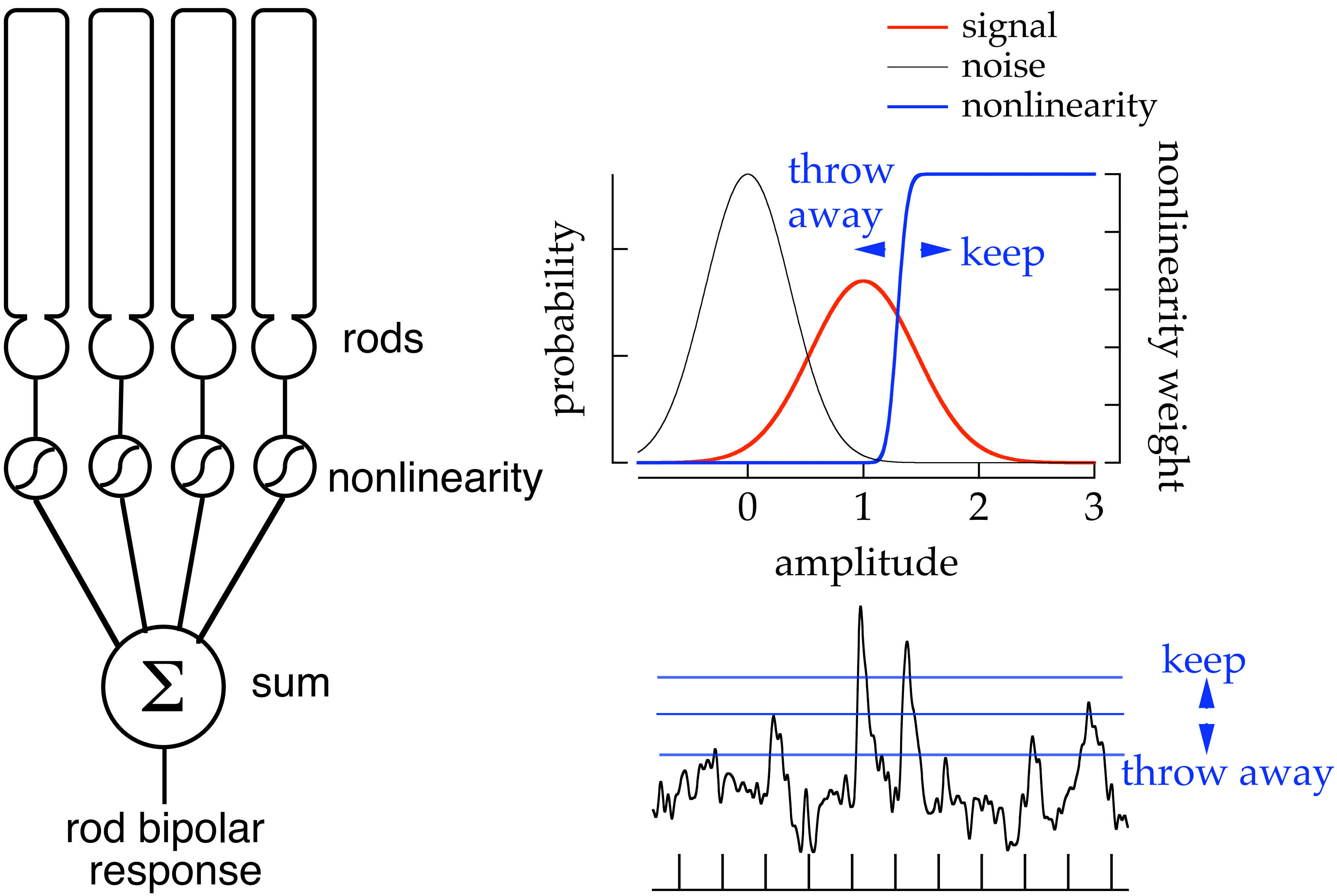


Field and Rieke, 2002

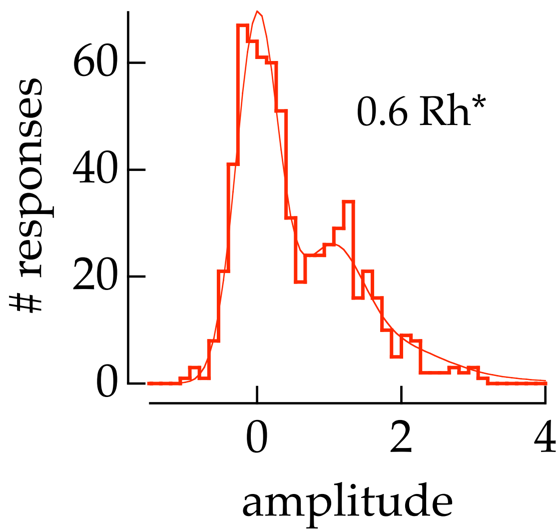
MODEL FOR ROD-ROD BIPOLAR SIGNAL TRANSFER



MANY OF ROD'S SINGLE PHOTON RESPONSES ELIMINATED IN ROD-ROD BIPOLAR SIGNAL TRANSFER

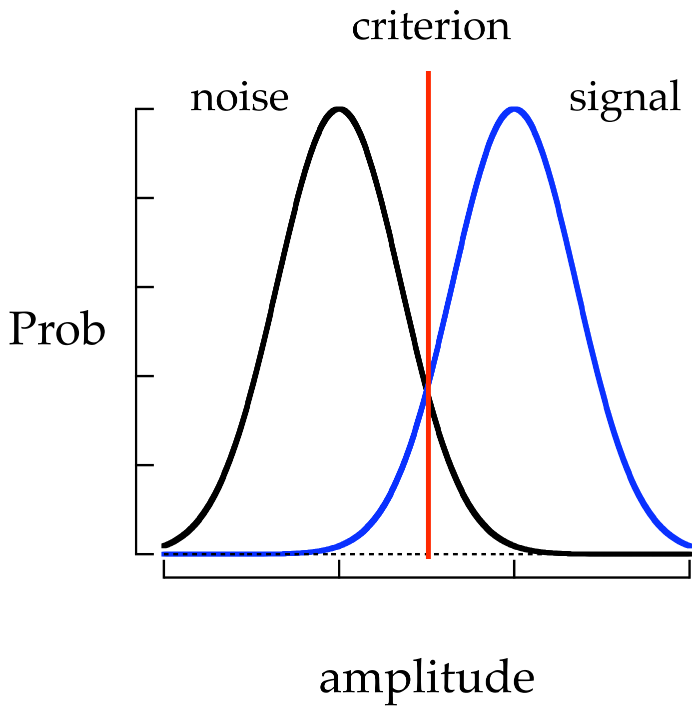


We are not remembering that the system operates at much lower light levels



... remember that moonless night!

A Bayesian framework applied to single photon detection

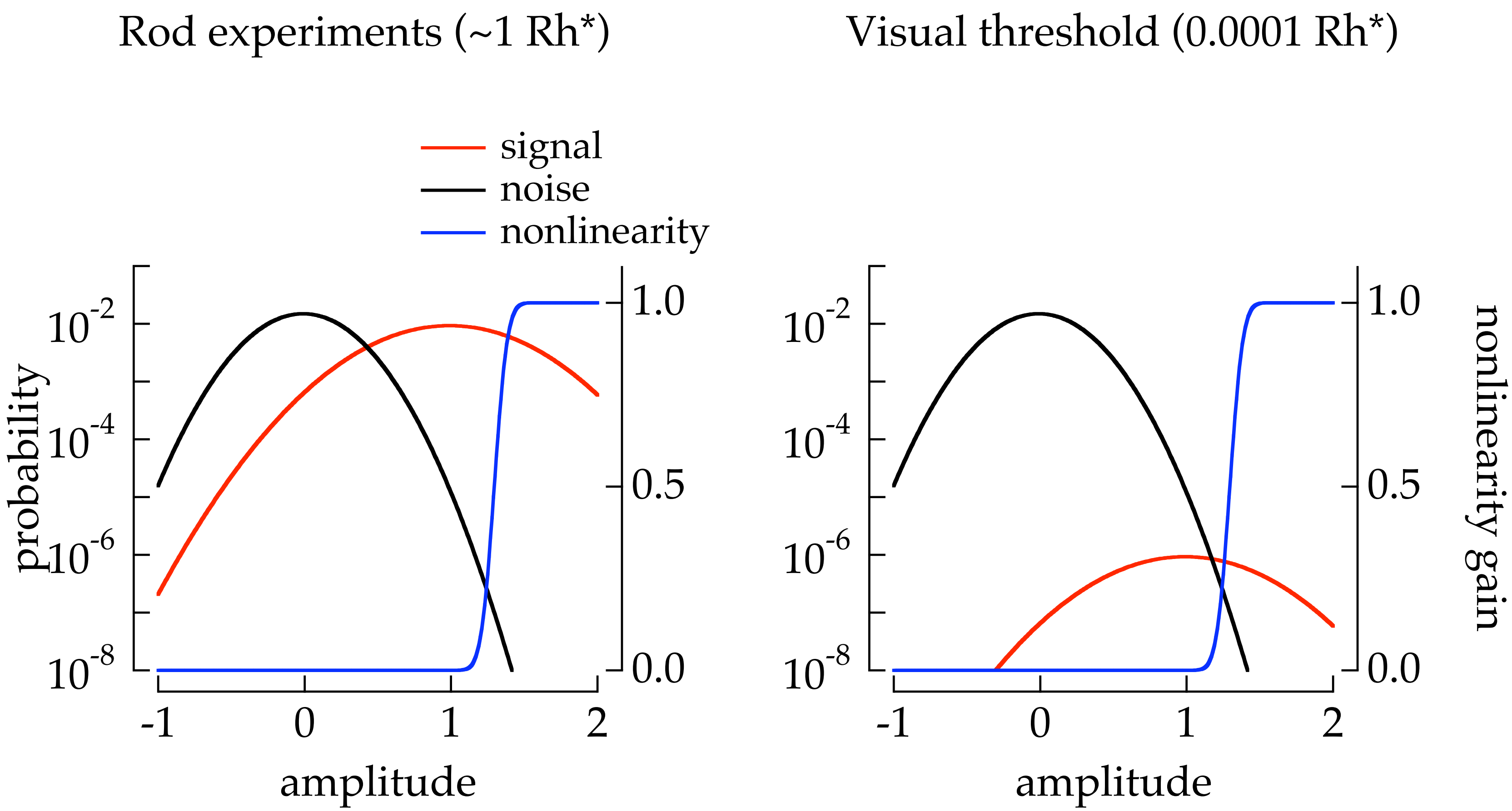


Imagine two distributions, where you are trying to minimize your overall error rate.

You are told that sampling from the "noise" distribution is 10,000 time more likely than sampling from the signal distribution

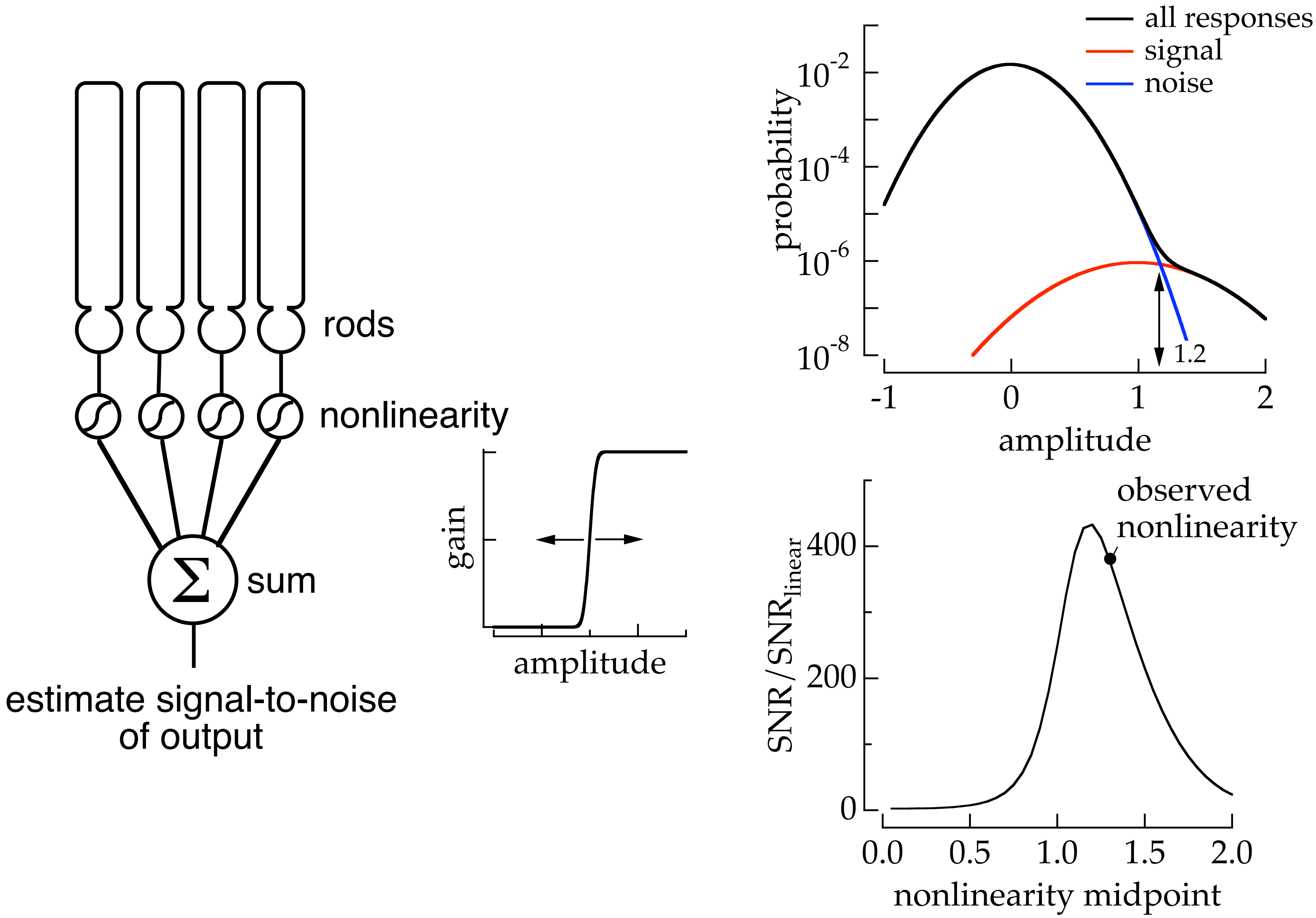
You should weight your evidence that a sample comes from a given distribution by this "prior"!

DISTRIBUTION OF ROD RESPONSES AT VISUAL THRESHOLD



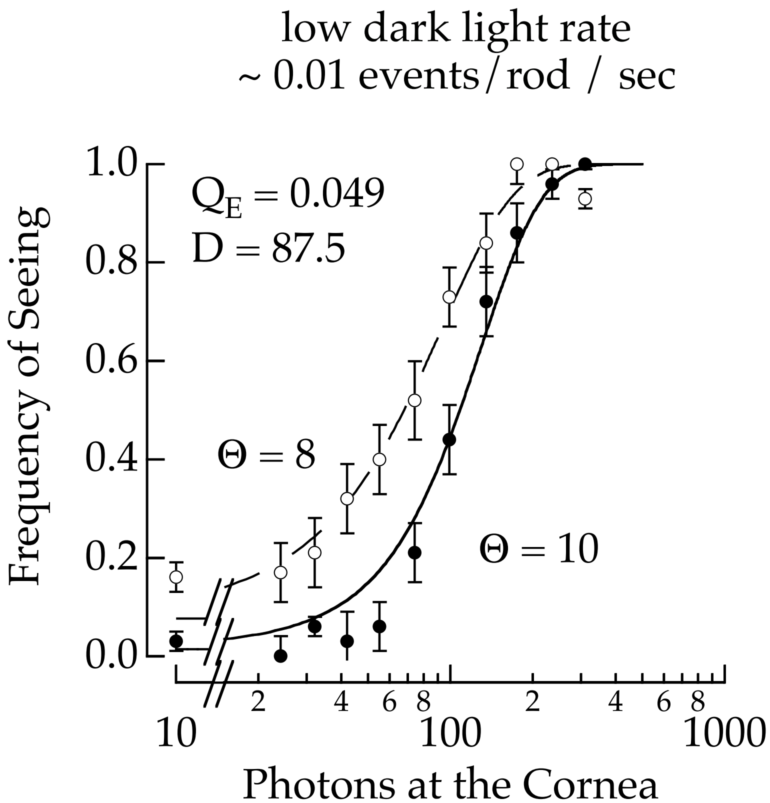
Prior probability of getting a photon very low!

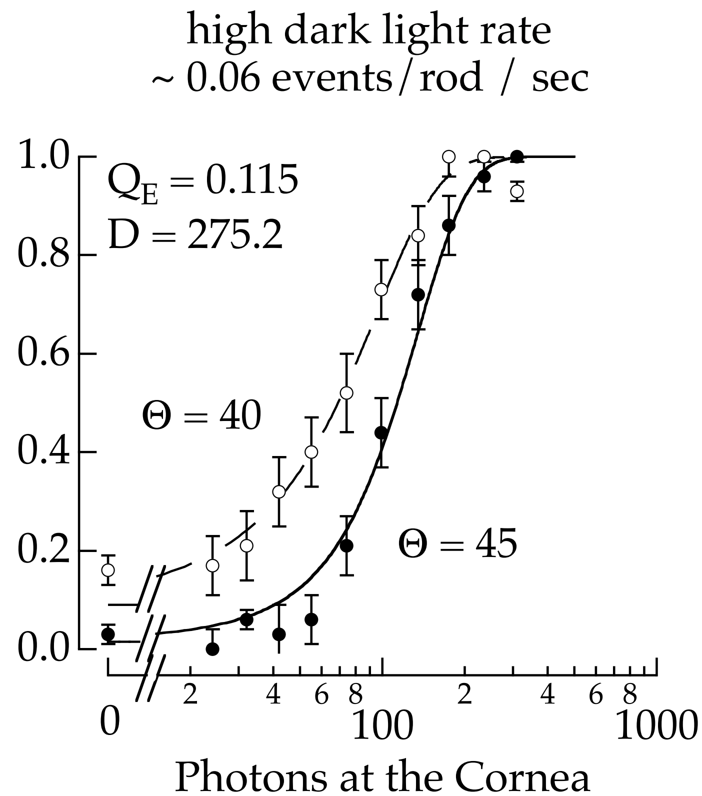
ROD BIPOLAR PROVIDES NEAR OPTIMAL READOUT OF ROD SIGNALS AT VISUAL THRESHOLD (0.0001 Rh*/rod/integration time)



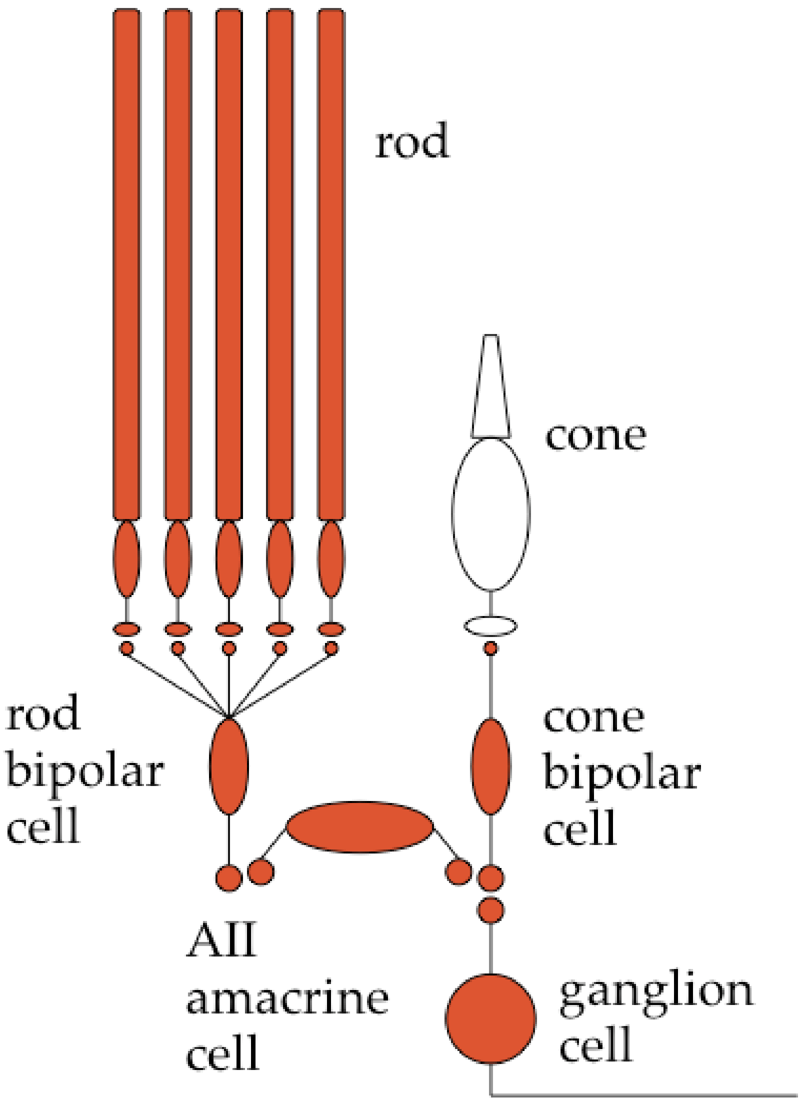
Field and Rieke, 2002

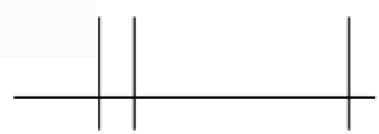
This nonlinearity may help to explain the low quantum efficiency



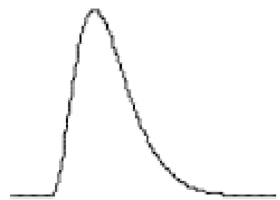


Detecting a sparse signal across many noisy detectors





- phototransduction:
  - single photons reliably transduced



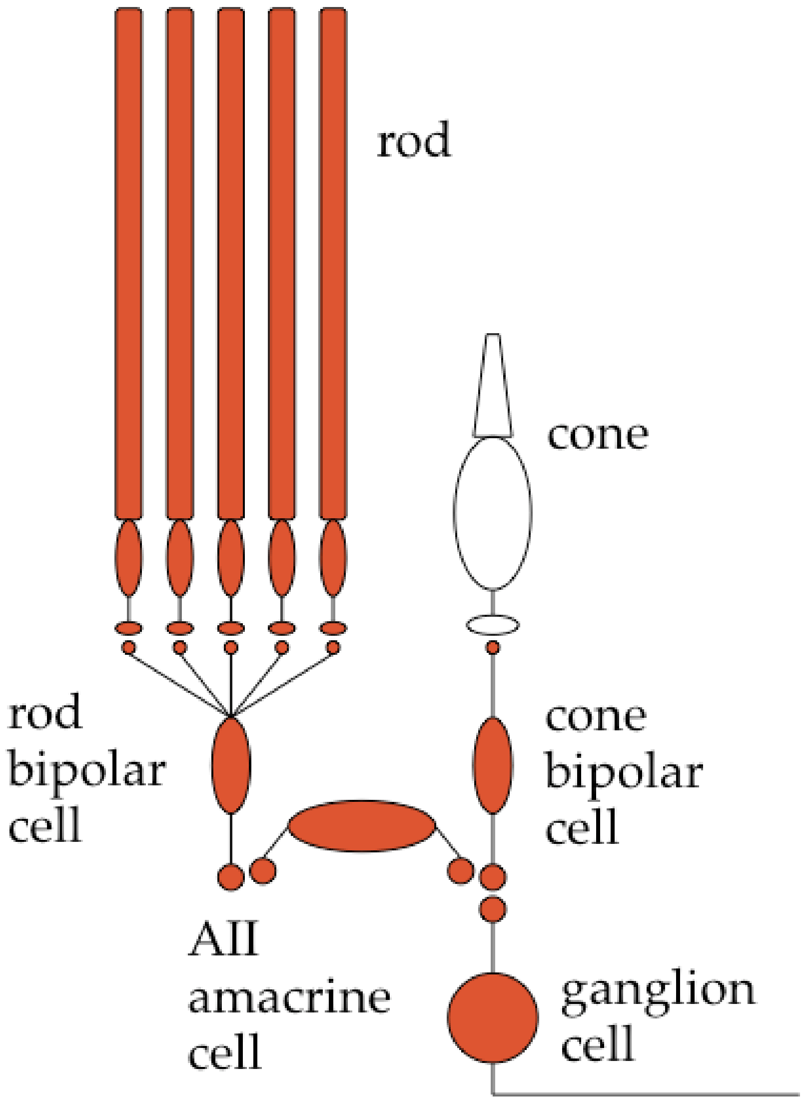
- synaptic transmission:
  - reliable transmission of single photon responses
- neural coding:
  absorption of a few photons produces change in optic nerve activity

Conclusions

Behavioral measurements of absolute threshold do not strongly constrain the efficiency of signal processing

Given the signal and noise properties of rod photoreceptors and the statistics of photon arrival, it appears that the bipolar cells are nearly optimally processing the rod signals.

Further Reading



Behavior

Hecht et al 1942

Sakitt 1972

Phototransduction:

Baylor et al 1979

Baylor et al 1984

Signal transmission

Field and Rieke 2002

Ganglion cells

Barlow et al 1971

Review

Field et al 2005

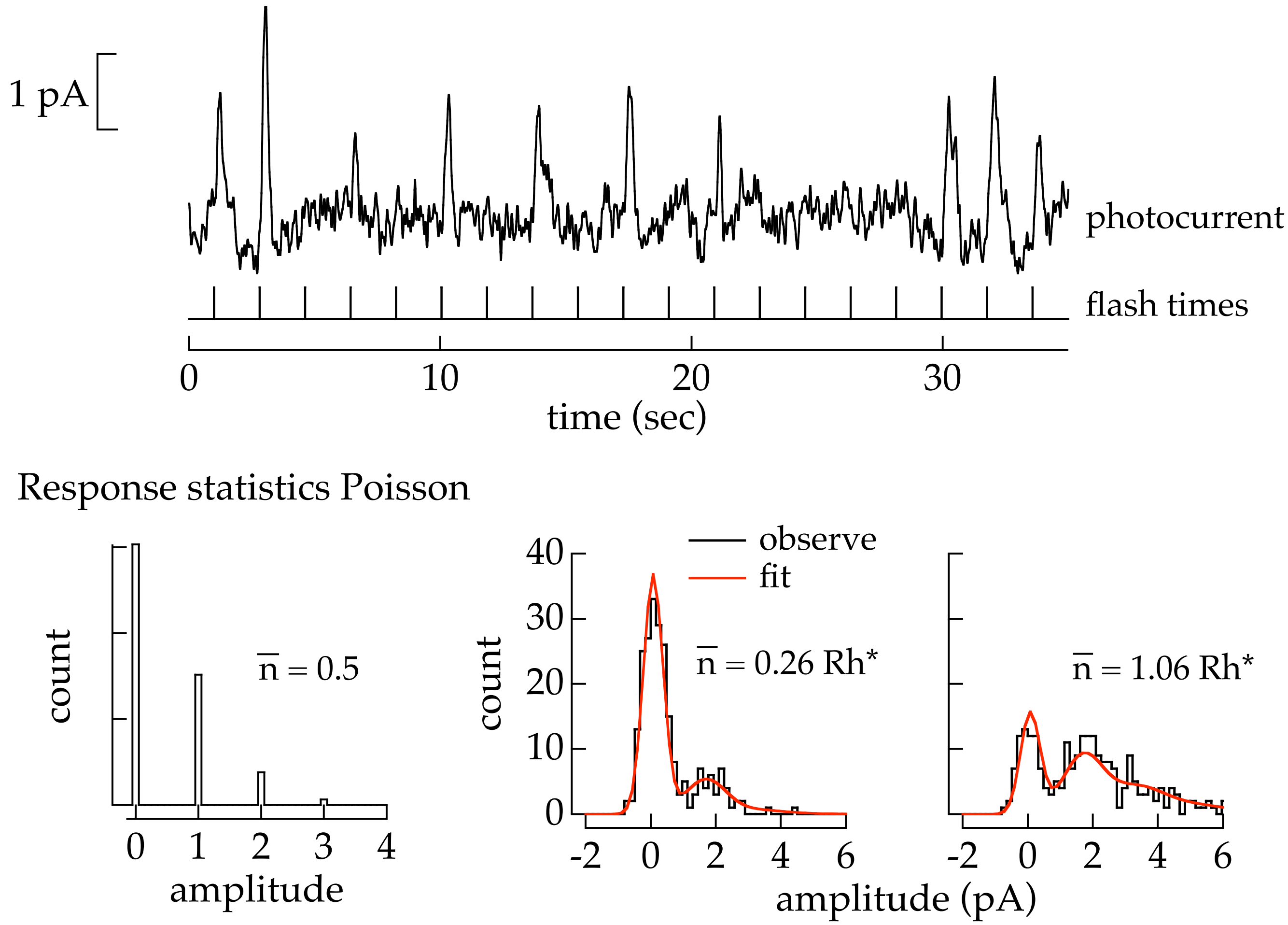
History

1905 Einstein proposes a quantum theory of light
1916 Millikan's experiments on photoelectric effect
1920 Lorentz estimates the number of photons required for detection
1921 Einstein wins Nobel Prize (photoelectric effect)
1923 Millikan wins Nobel Prize (photoelectric effect)
1942 Hecht *et al.* "show" retina requires ~5 photon absorptions
1971 Barlow *et al.* measure cat ganglion cell response to single photons
1979 Baylor *et al.* measure rod response to single photons.

Primate rod photoreceptor signal and noise

Responses to a repeated flash are quantized

Response statistics Poisson



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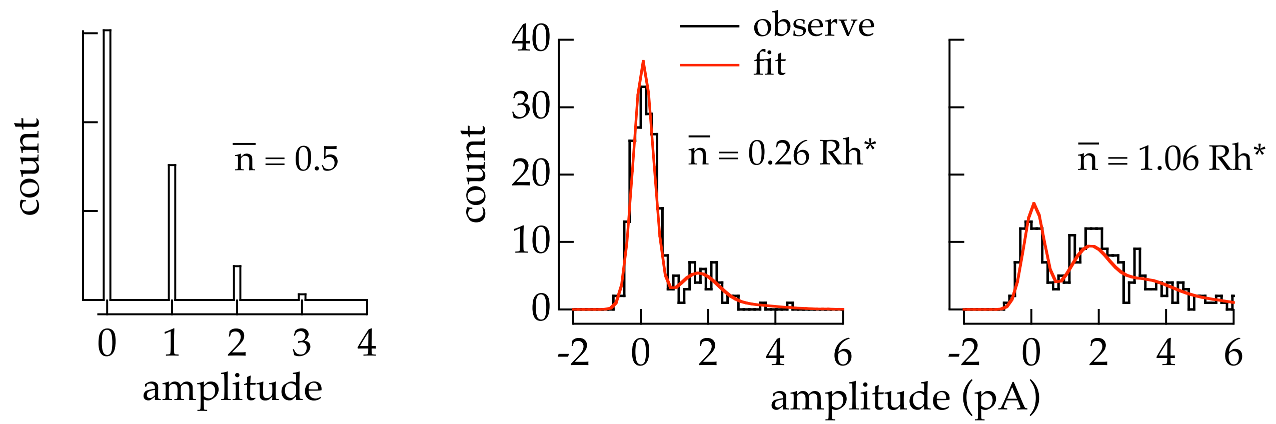

$$P(A) = \sum_{n=0}^{\infty} \text{Poisson}(n|\bar{n}) \text{Gaussian}(A|\bar{A}, \sigma_D, \sigma_A)$$

$$P(A) = \sum_{n=0}^{\infty} \frac{\exp(-\bar{n})\bar{n}^n}{n!} \left[2\pi \left(\sigma_D^2 + n\sigma_A^2\right)\right]^{-1/2} \exp\left(-\frac{(A - n\bar{A})^2}{2(\sigma_D^2 + n\sigma_A^2)}\right)$$