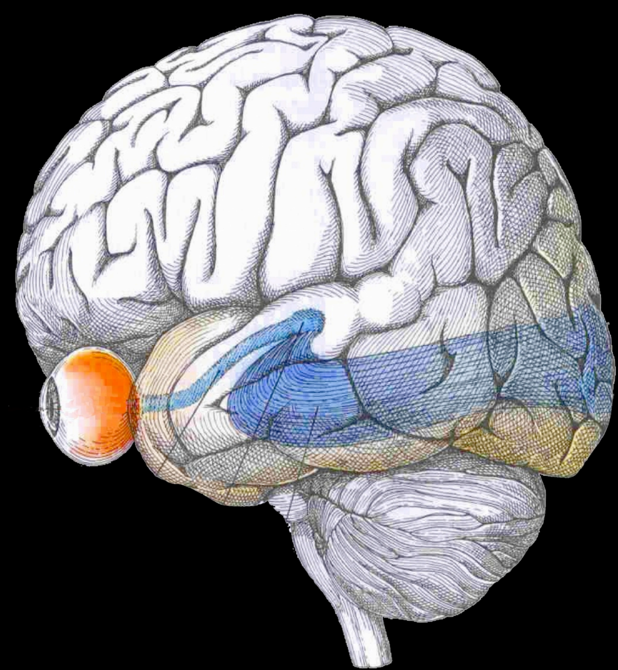
Models of visual neuron function

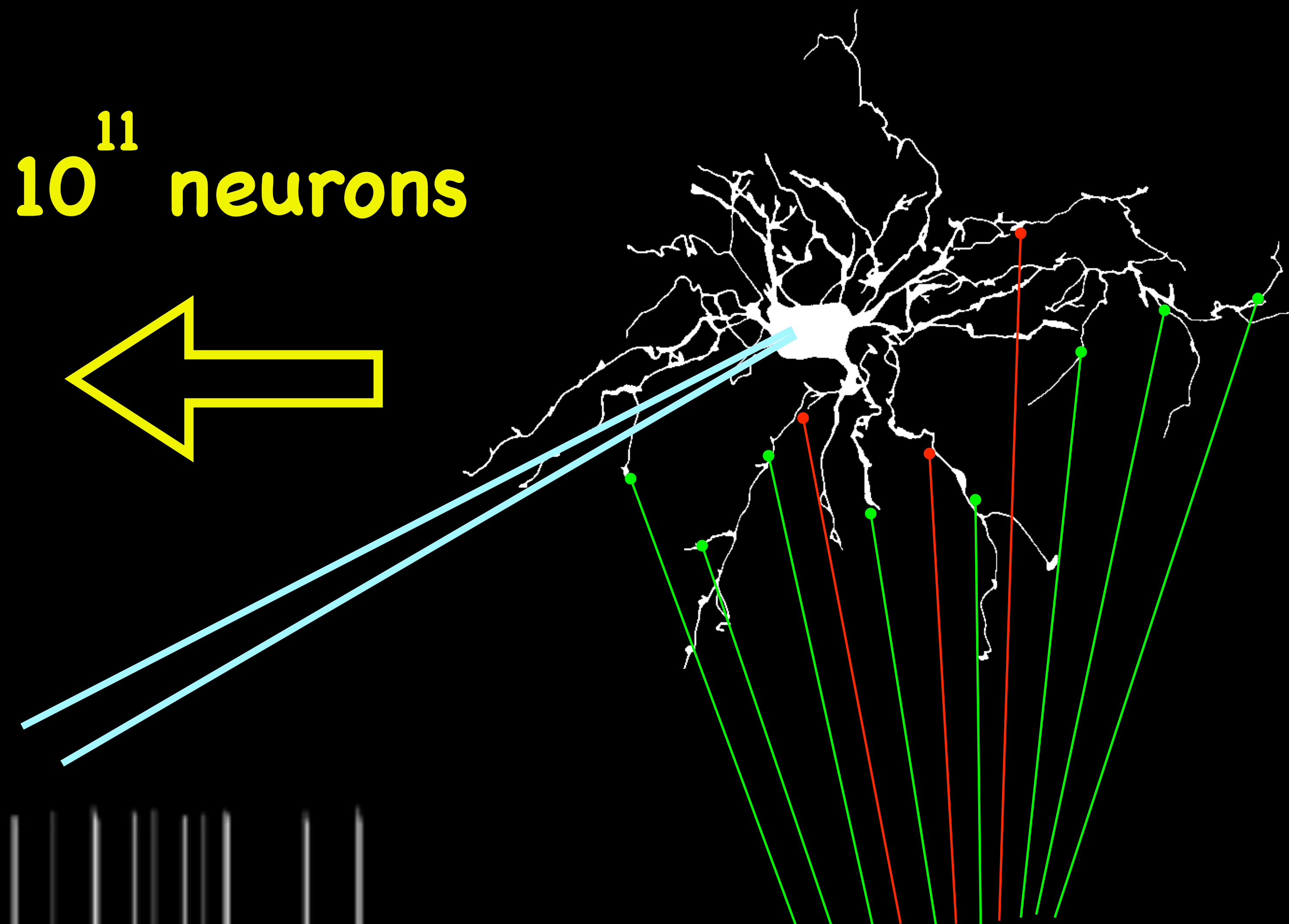
Quantitative Biology Course Lecture

Dan Butts

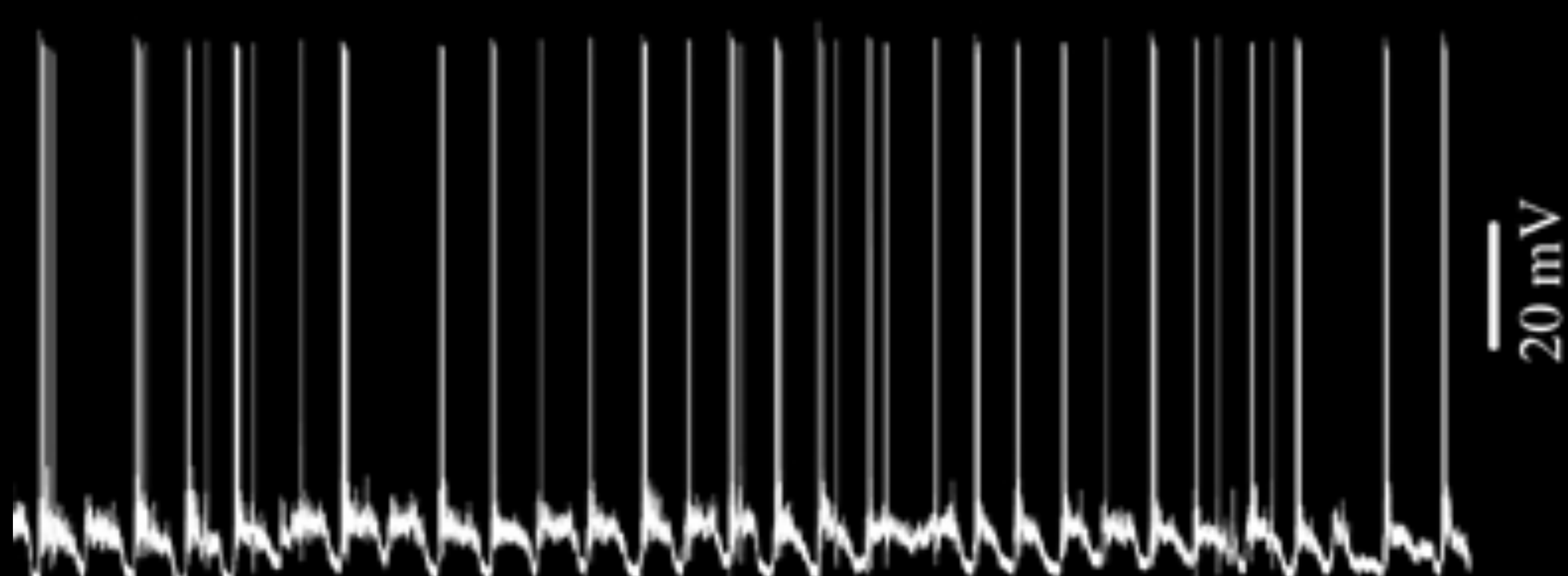
What is the "neural code"?



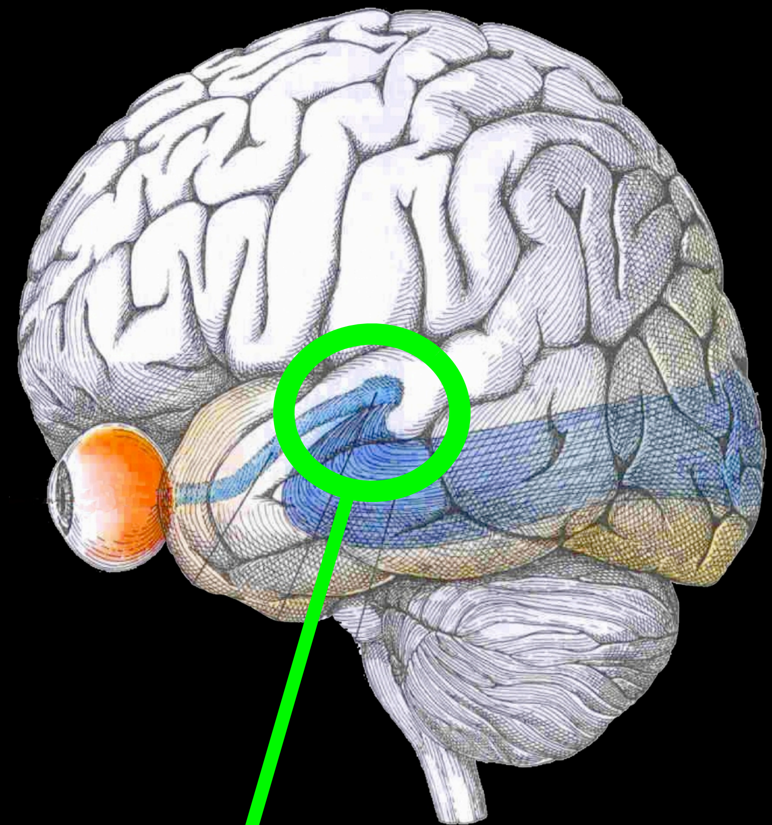
10^{11} neurons

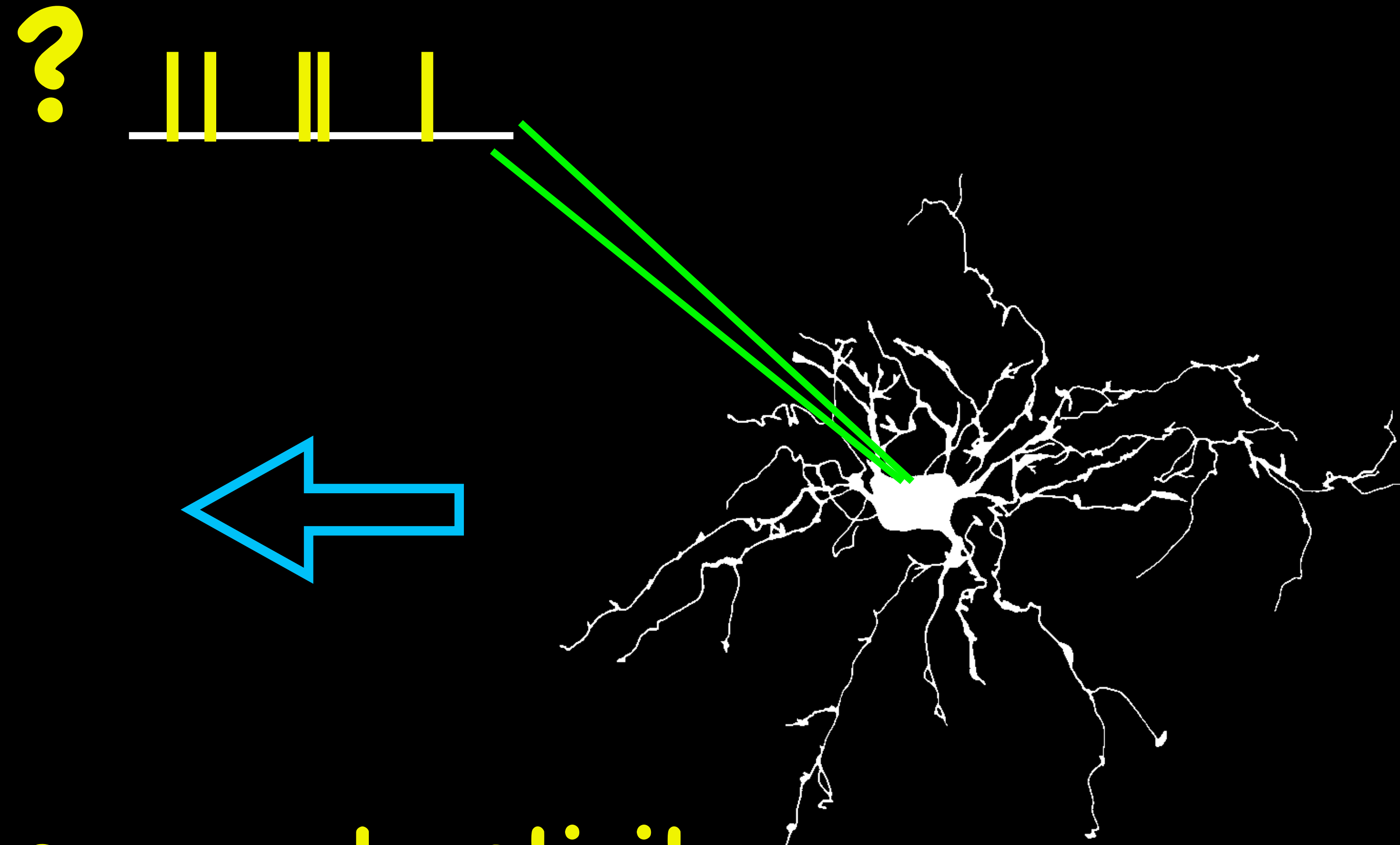


1,000-10,000 inputs



Electrical activity: nerve impulses





How does neural activity relate to brain function?

Use visual system:

Well characterized

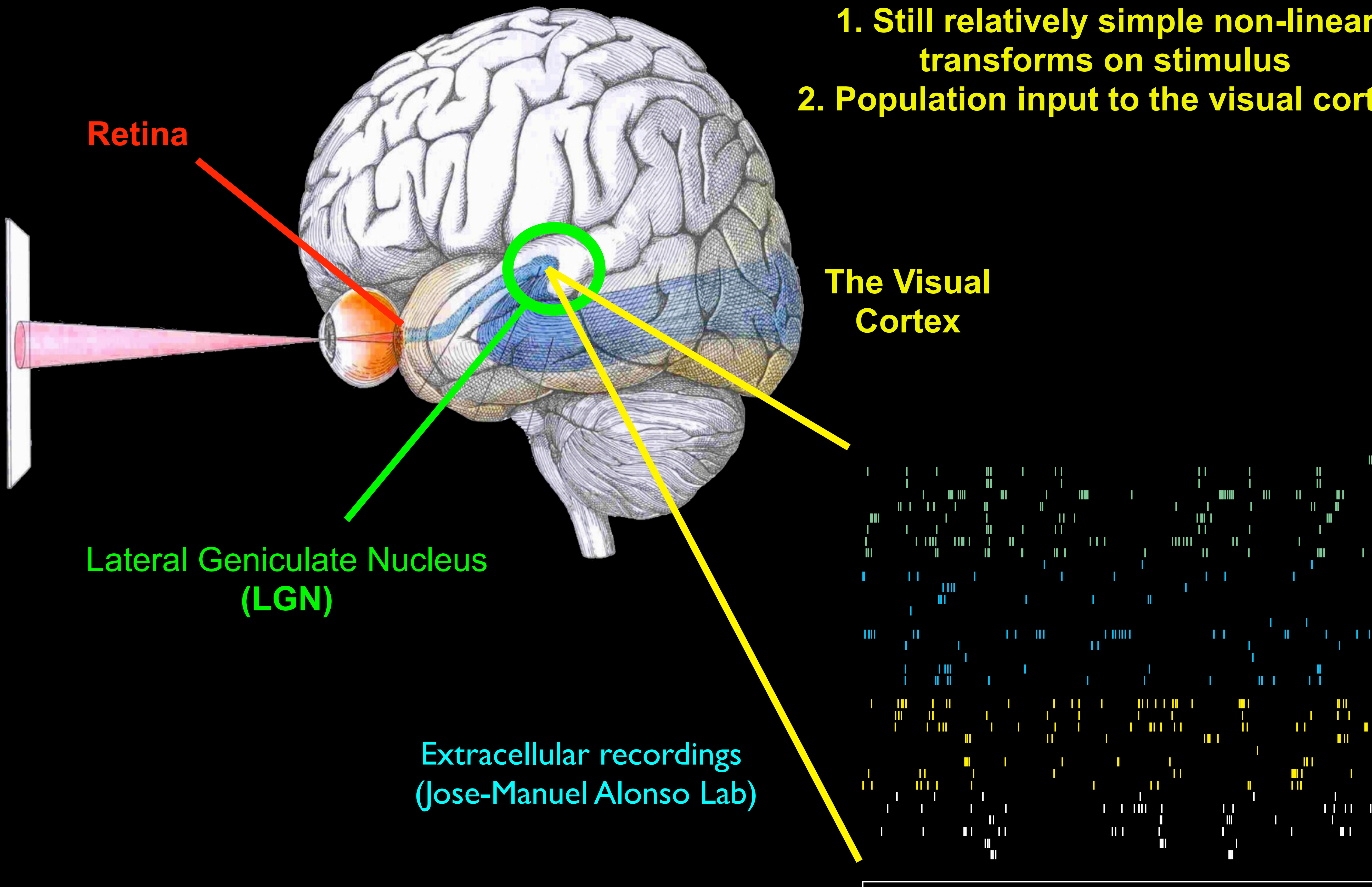
Intuitive function

Population input to the cortex

Lateral Geniculate Nucleus
(LGN)

Starting point: recordings in the LGN

1. Still relatively simple non-linear transforms on stimulus
2. Population input to the visual cortex

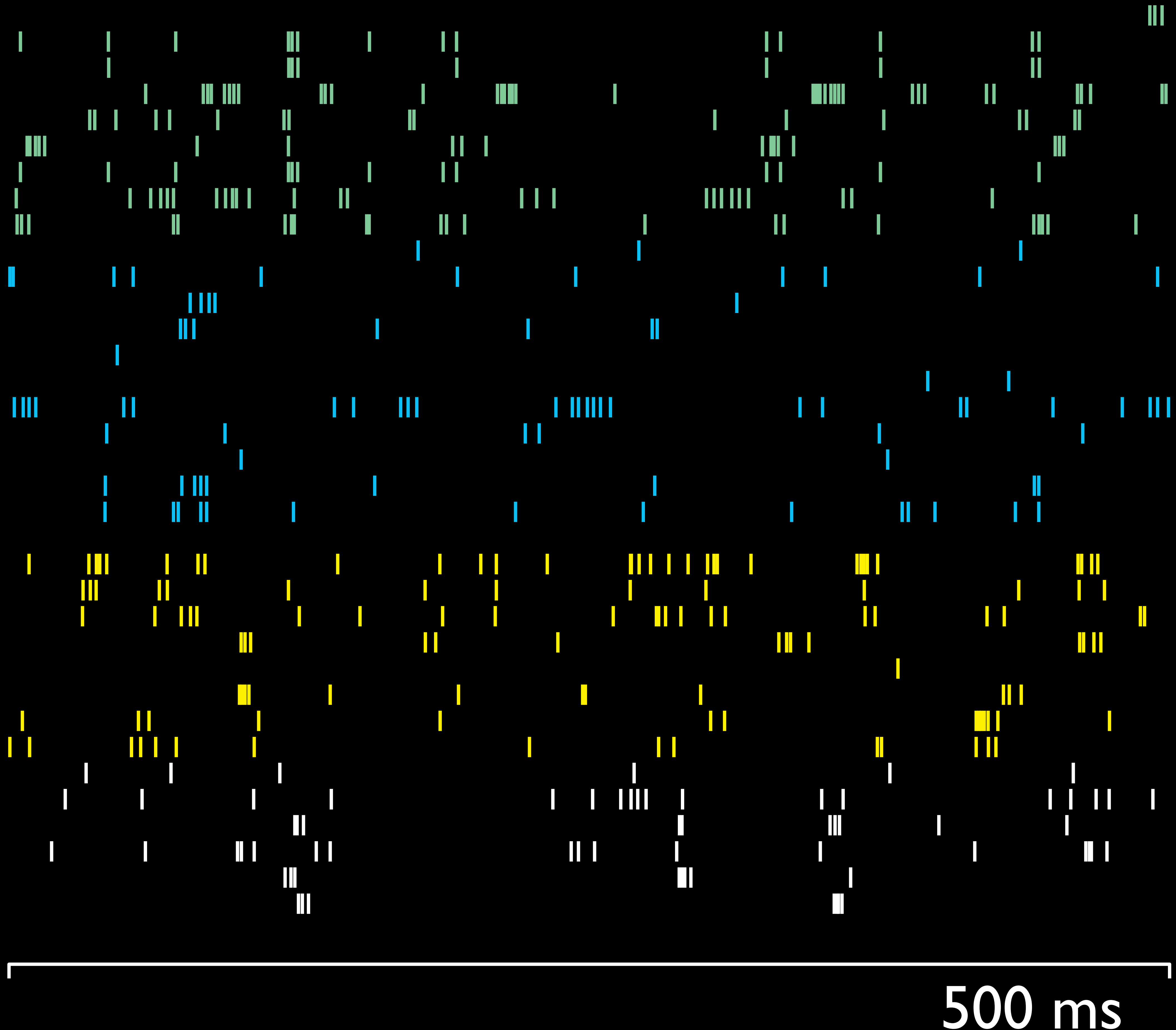


Visual stimulus

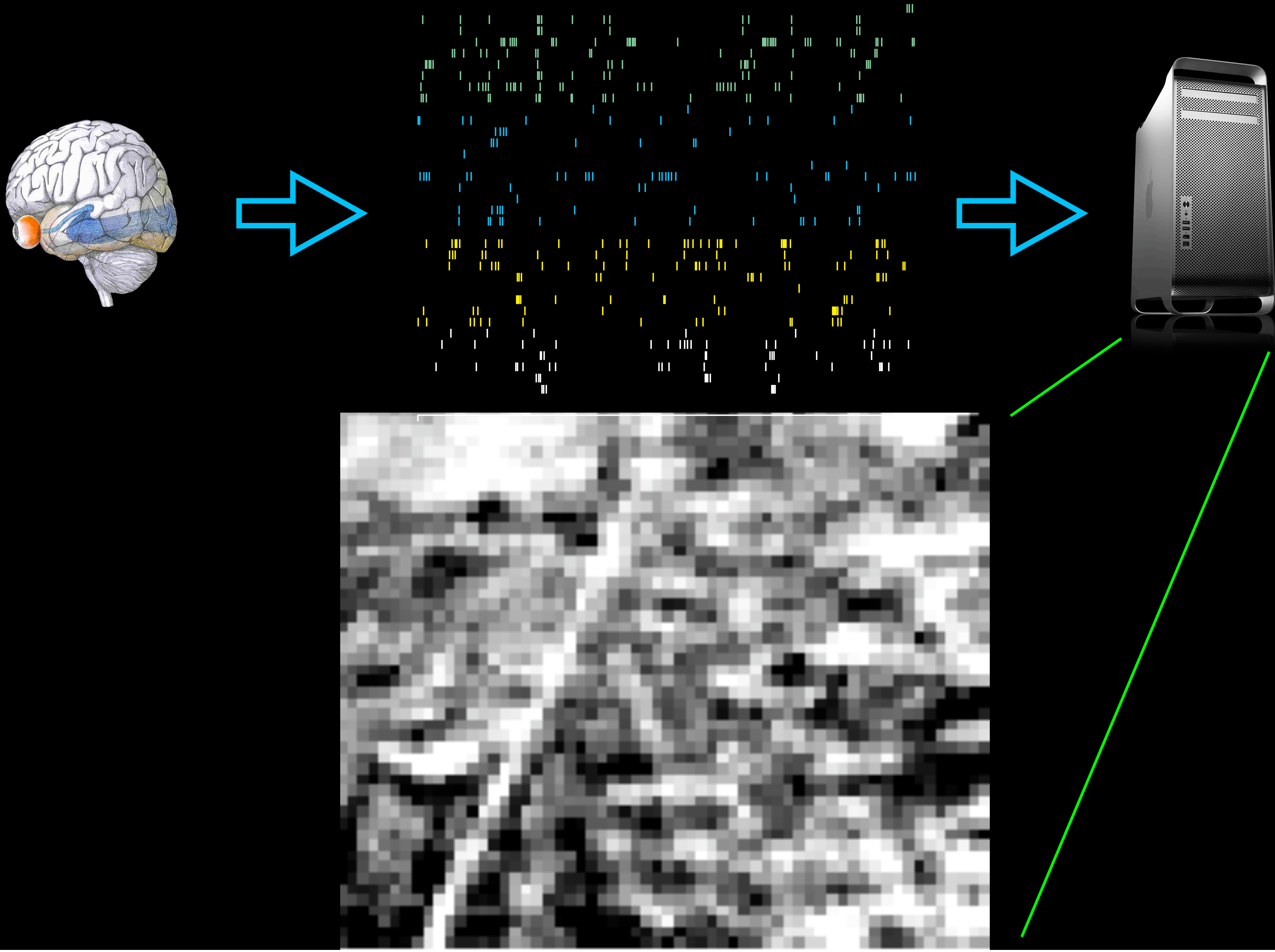
"Cat-cam" movies from Peter Koenig's Lab

(Kayser et al, 2004)

LGN neuron responses



Understanding and Decoding Neural Signals



Outline

1. Introduction to "receptive fields"

2. Building a visual neuron model

The LN (Linear-Non-linear) model

3. The problem of temporal precision and the need for new statistical methods

Maximum-likelihood modeling

4. **Research:** Application of maximum-likelihood modeling to explain precise timing of neuronal responses

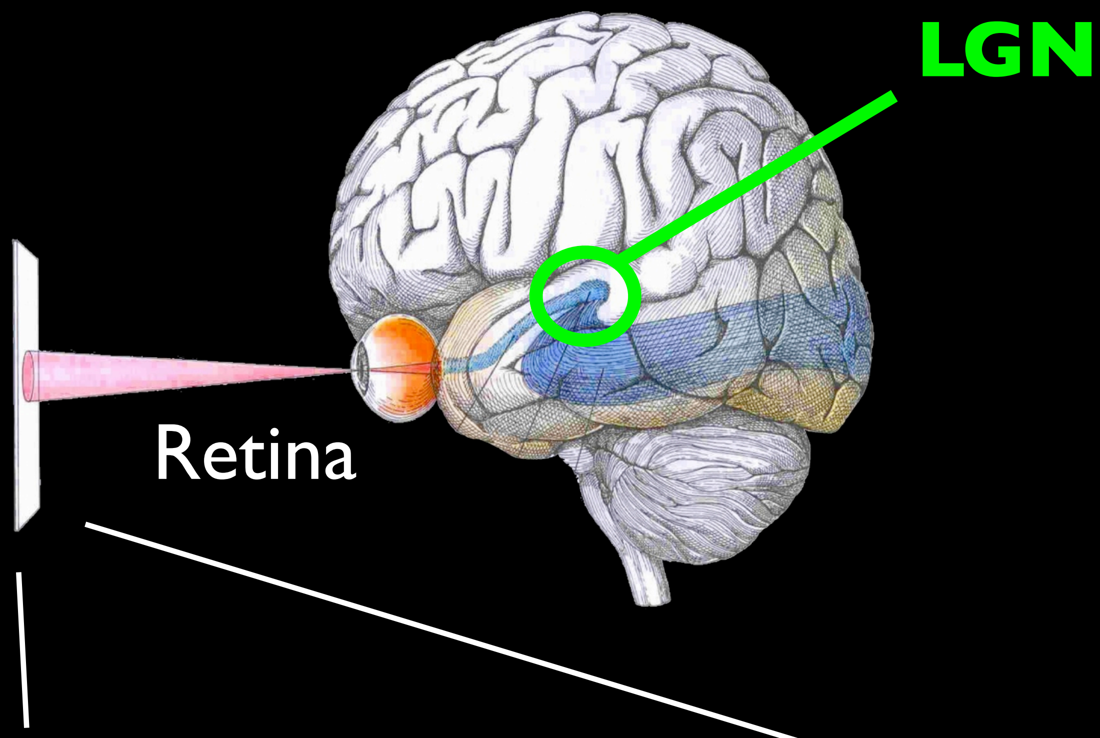
Coding like the muscle

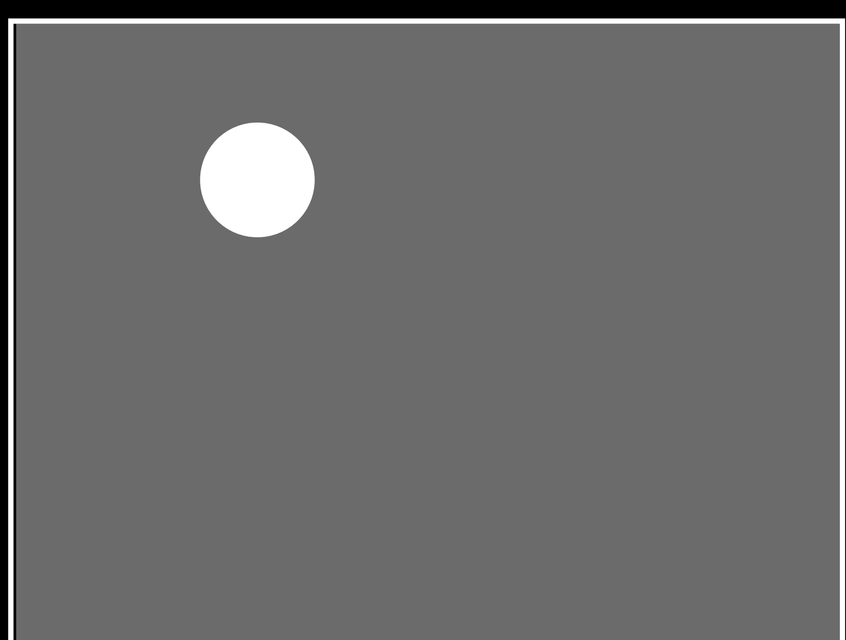
Muscle picture
with motoneuron

Little
contraction

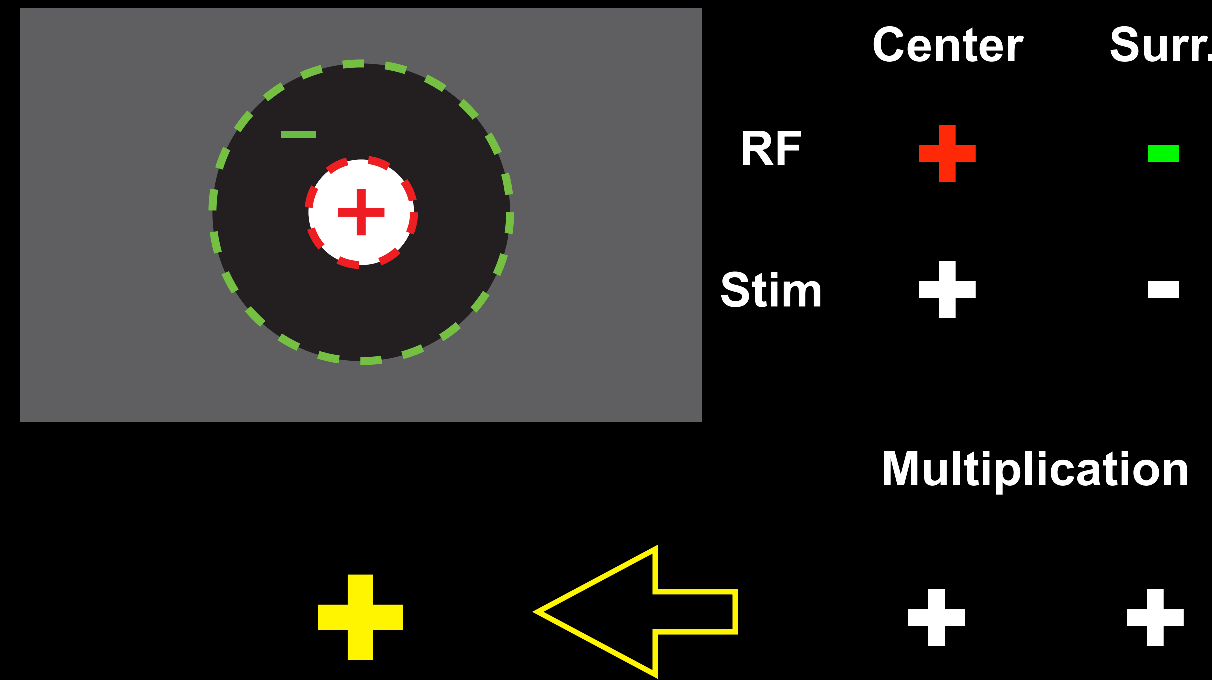
Lots of
contraction

The receptive field





Spatial stimulus

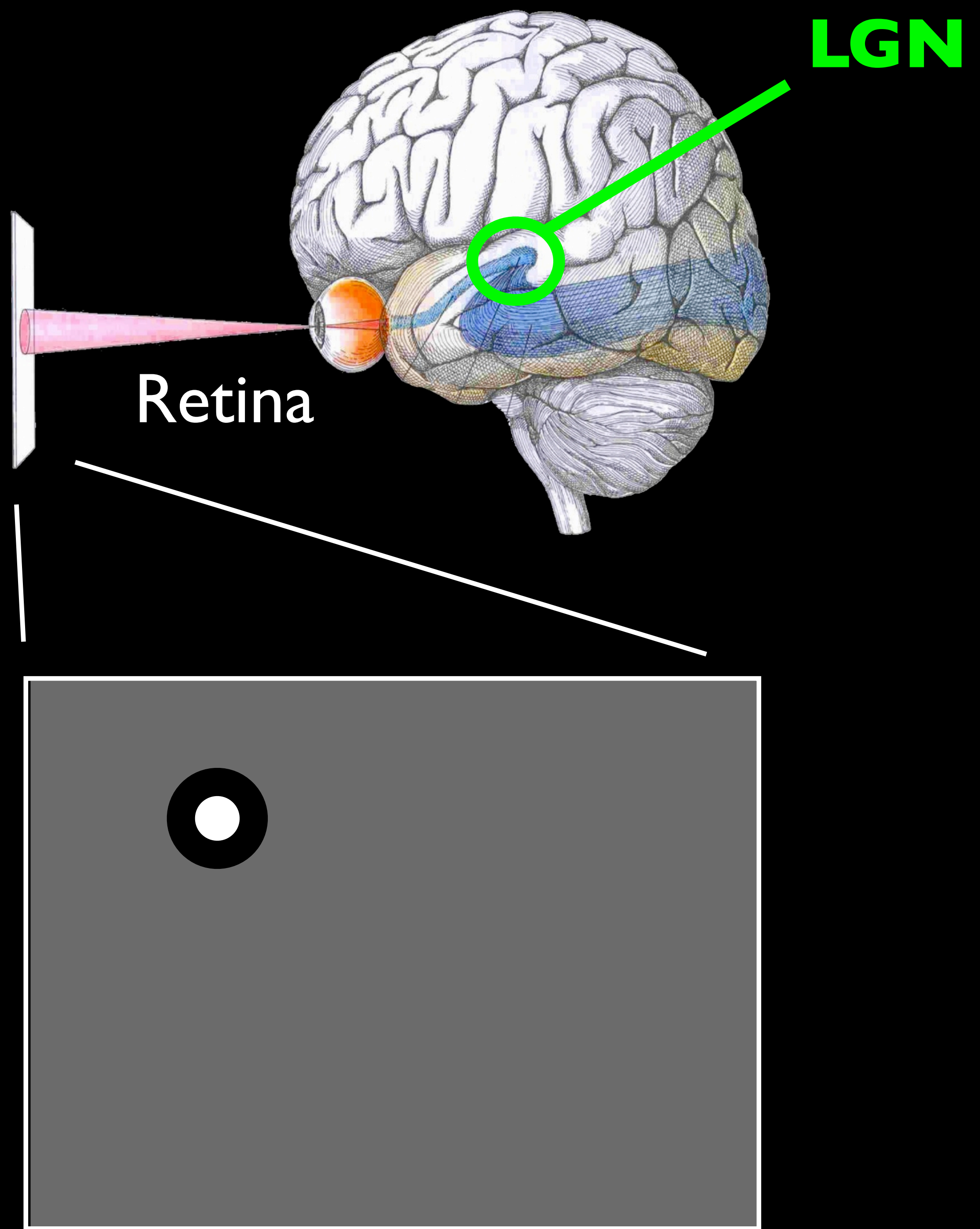


LGN responses related to how much the stimulus matches the receptive field

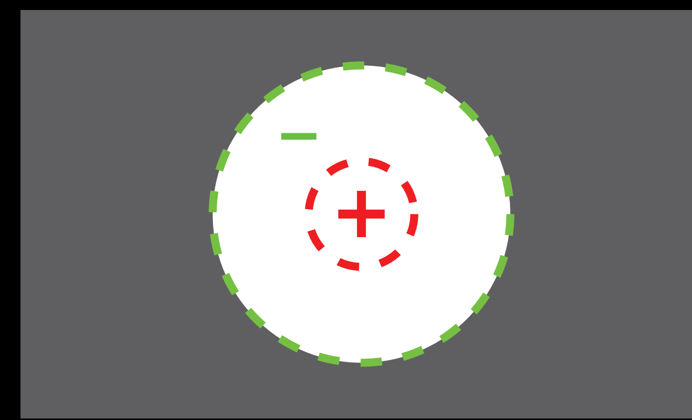
Linear comparison:

$$R = \sum_{\vec{x}} K_{sp}(\vec{x})\, S(\vec{x})$$

The receptive field



Spatial stimulus



	Center	Surr.
RF	+	-
Stim	+	+

Multiplication

0 ⇐ + -

LGN responses related to how much the stimulus matches the receptive field

Linear comparison:

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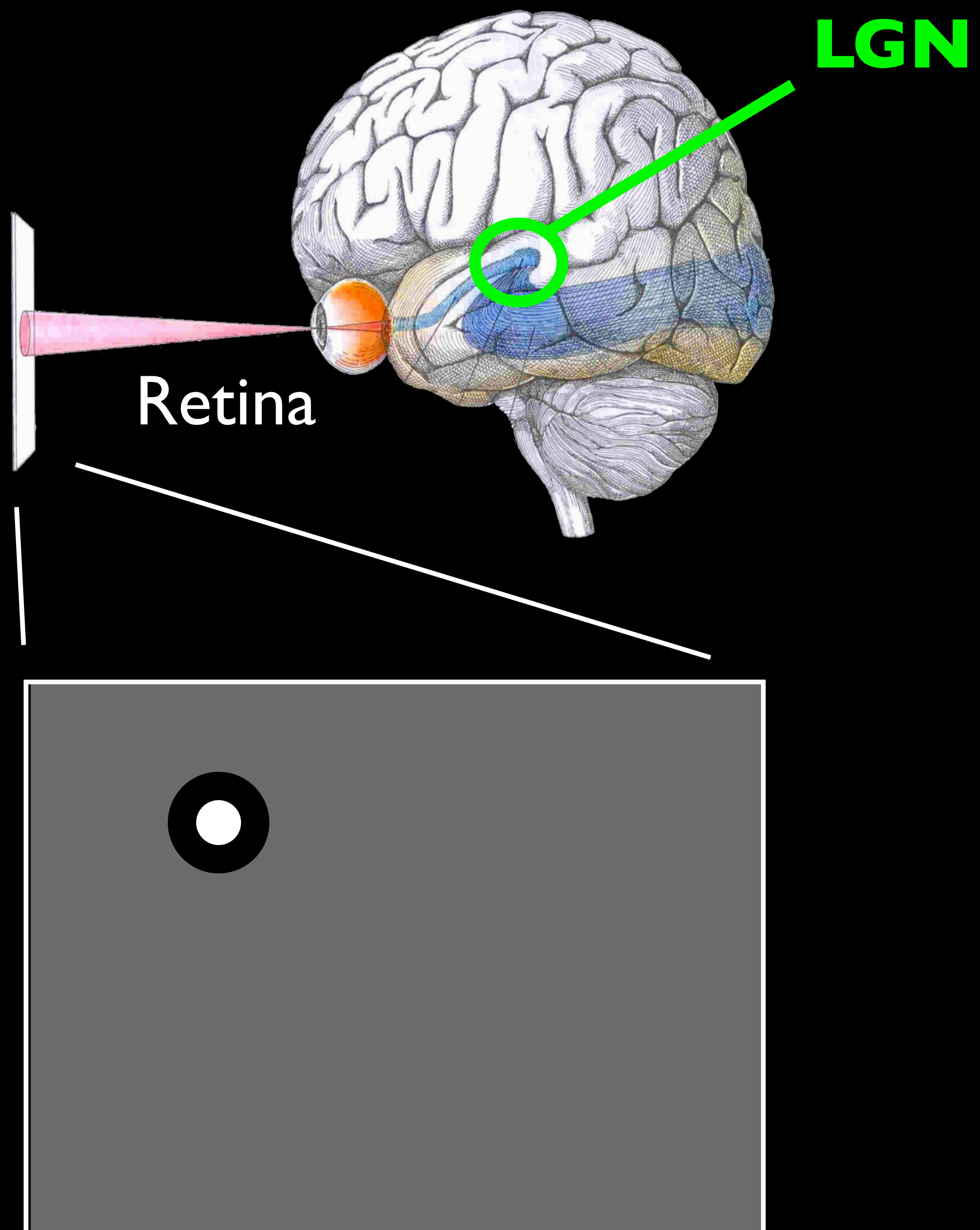
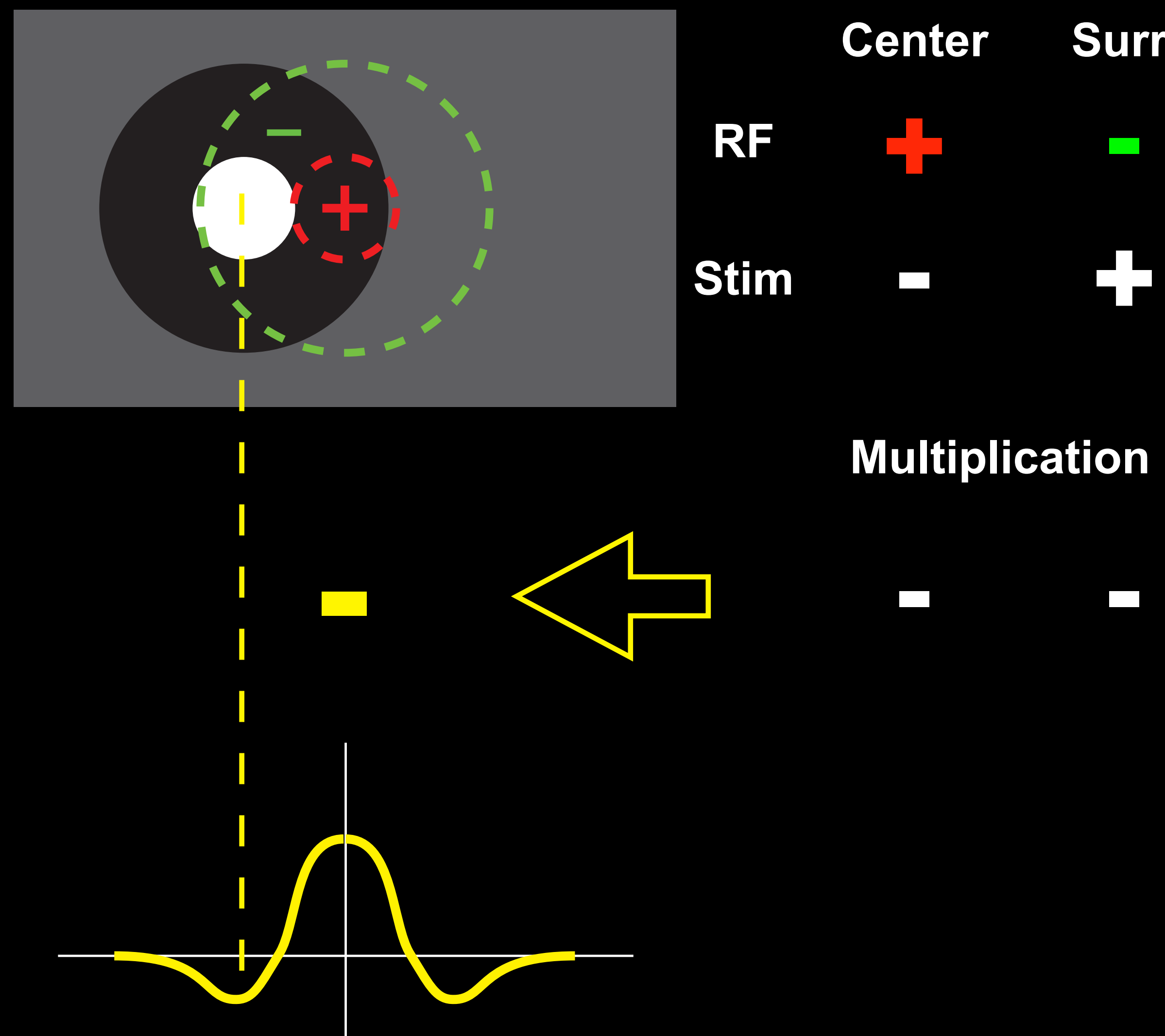
The receptive field



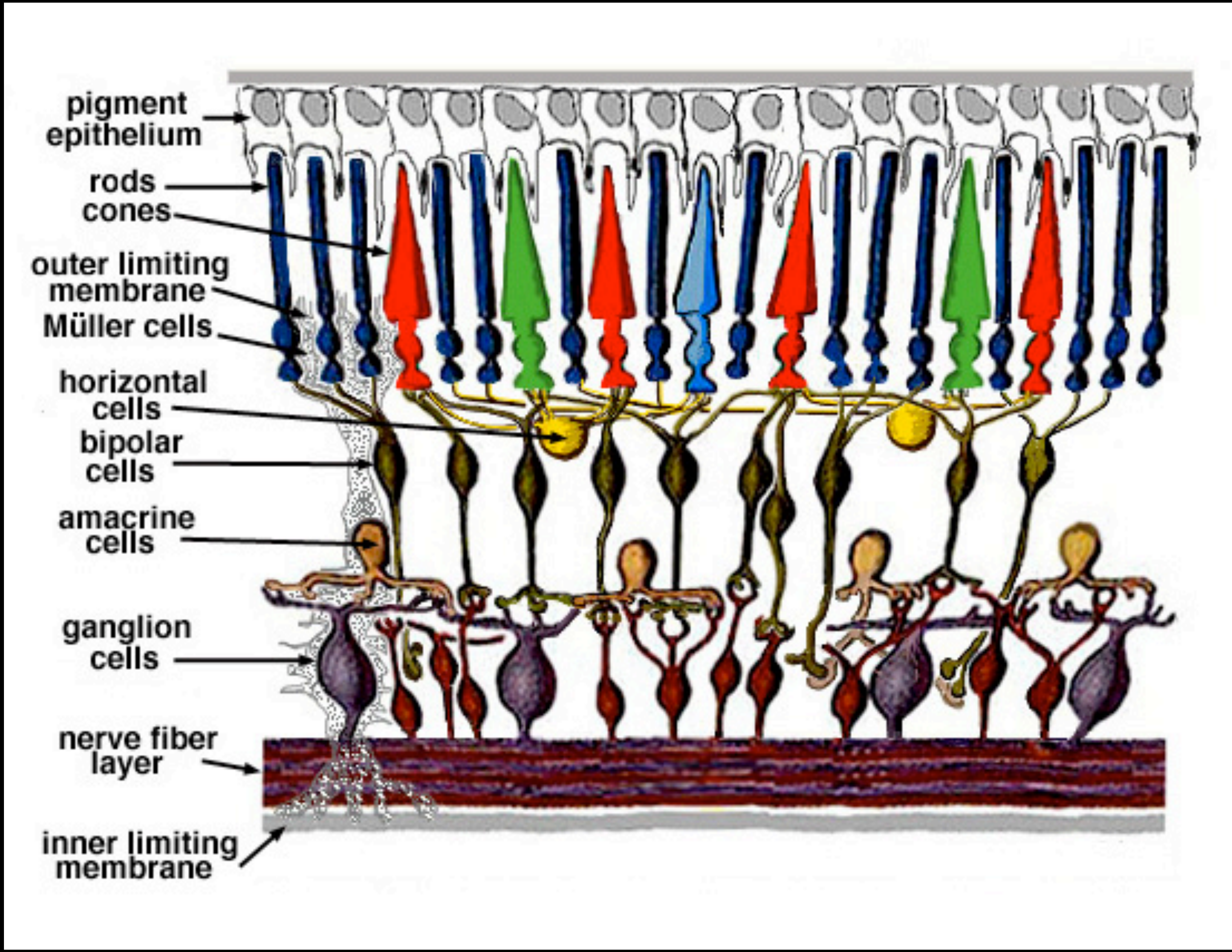
Spatial stimulus



Spatial features of image matter in relation to RF

Neuron is tuned for a given stimulus over a certain range.

Circuitry of the retina



...but vision involves motion

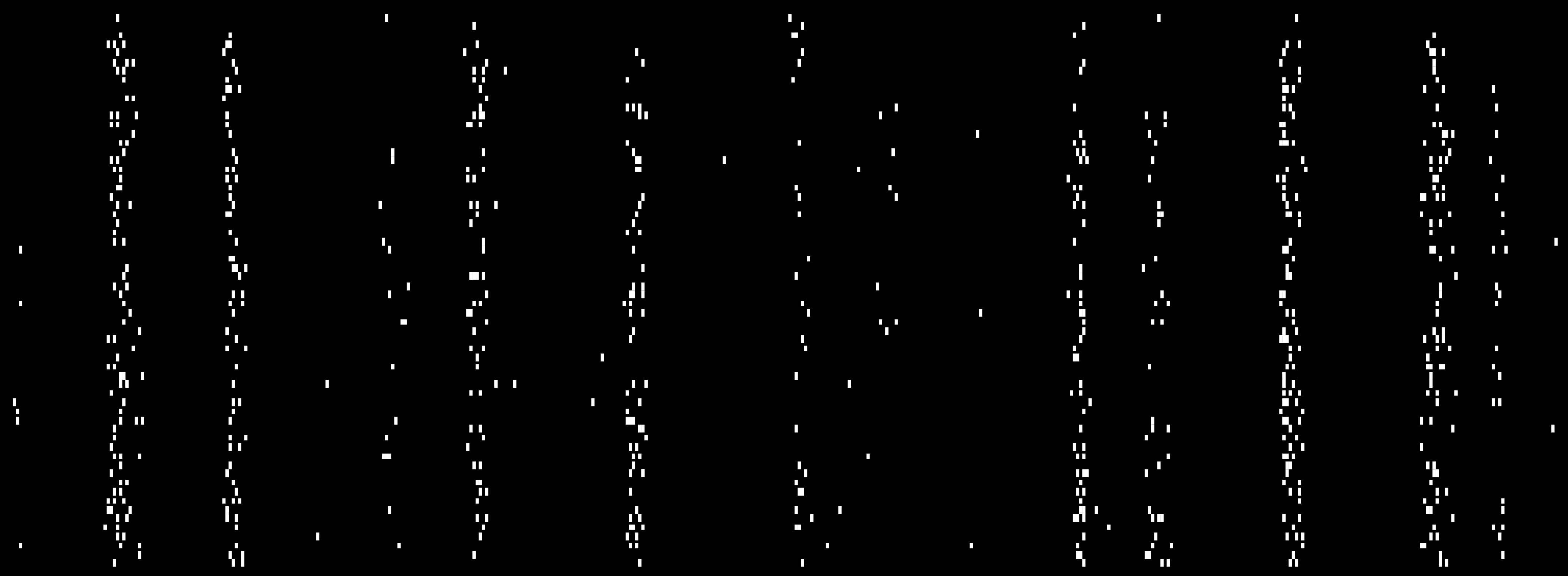
Motion in the visual scene/ self motion

Eye movements

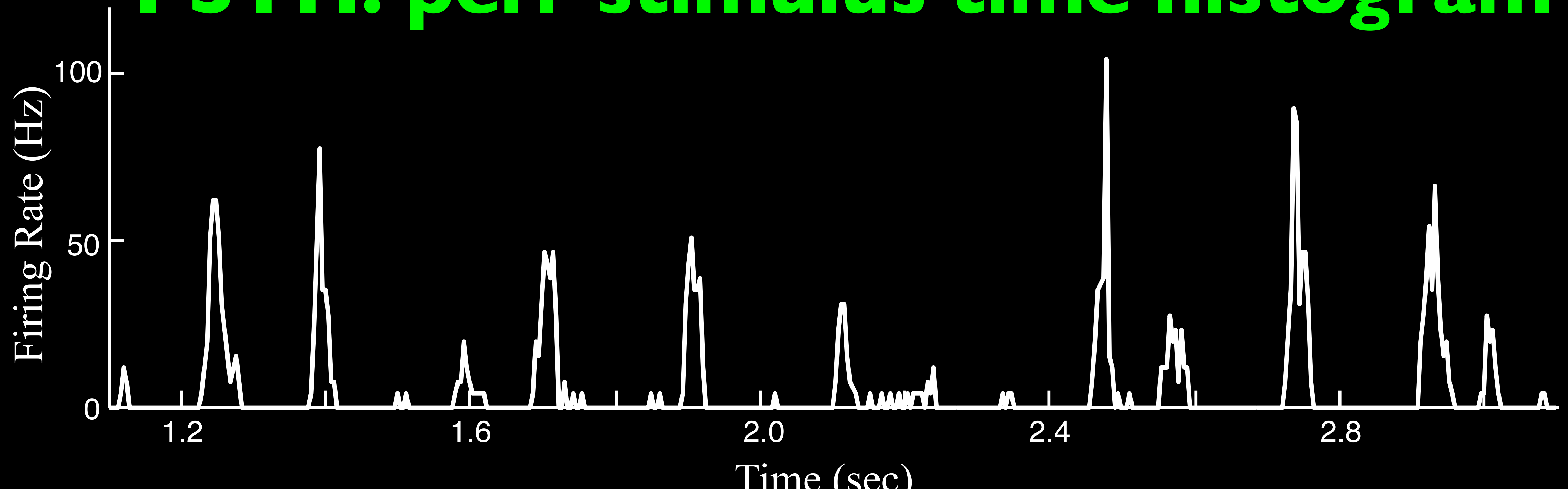
- saccades, microsac.
- ocular drift

LGN response during movie

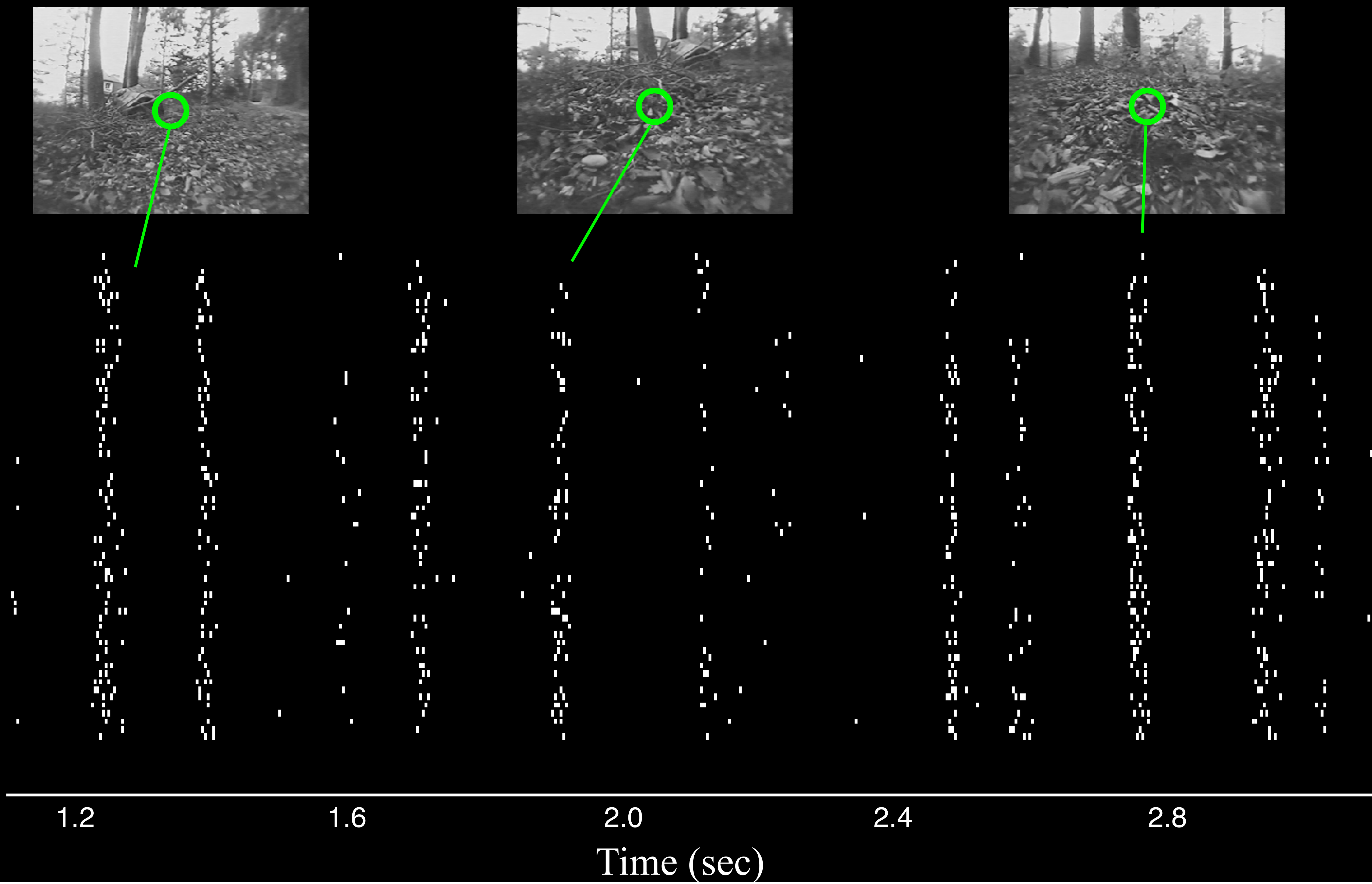
Raster plot



PSTH: peri-stimulus time histogram

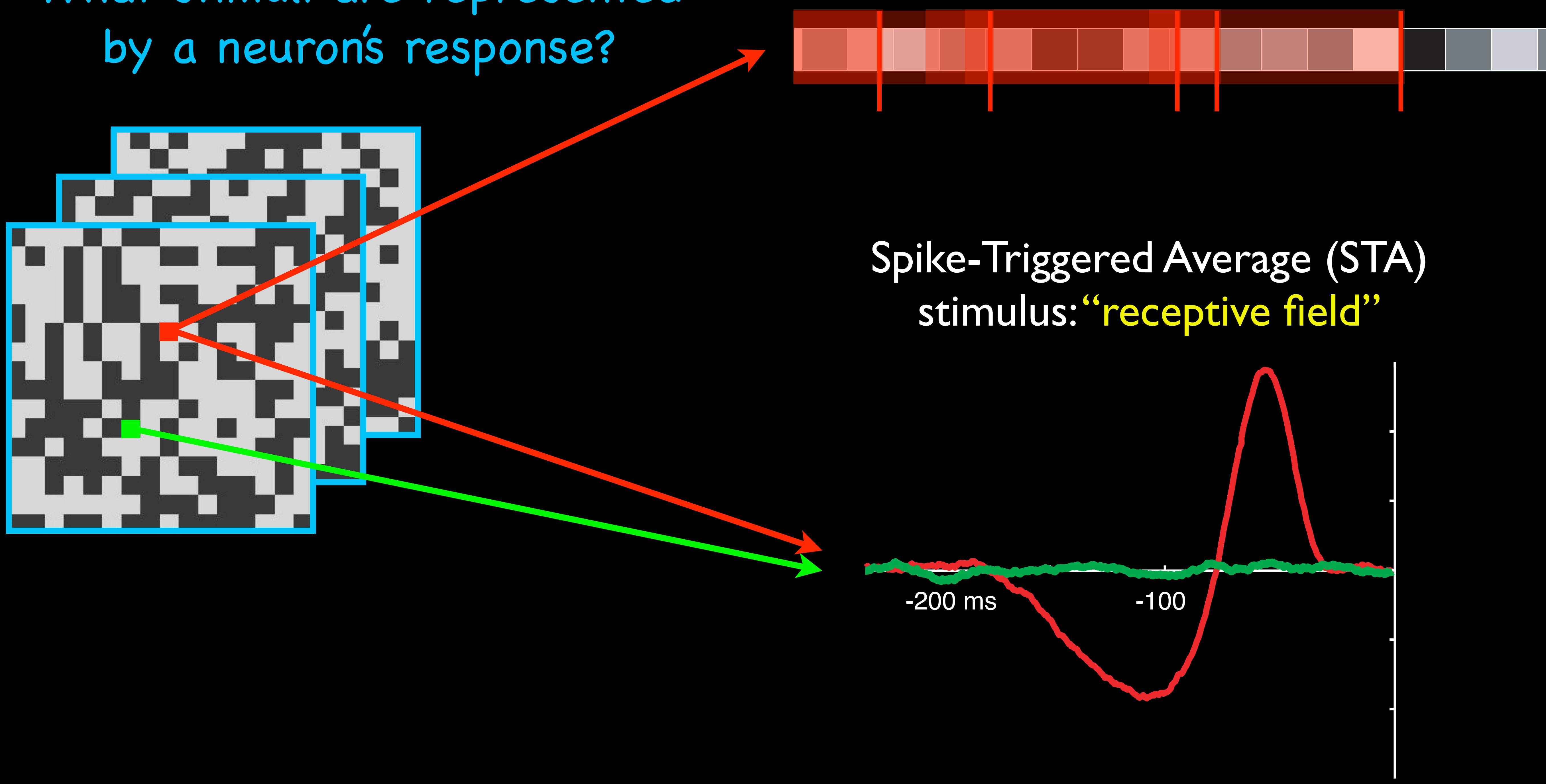


What does neural activity look like during a time-varying stimulus?



Visual neuron function: the spatiotemporal receptive field

What stimuli are represented by a neuron's response?



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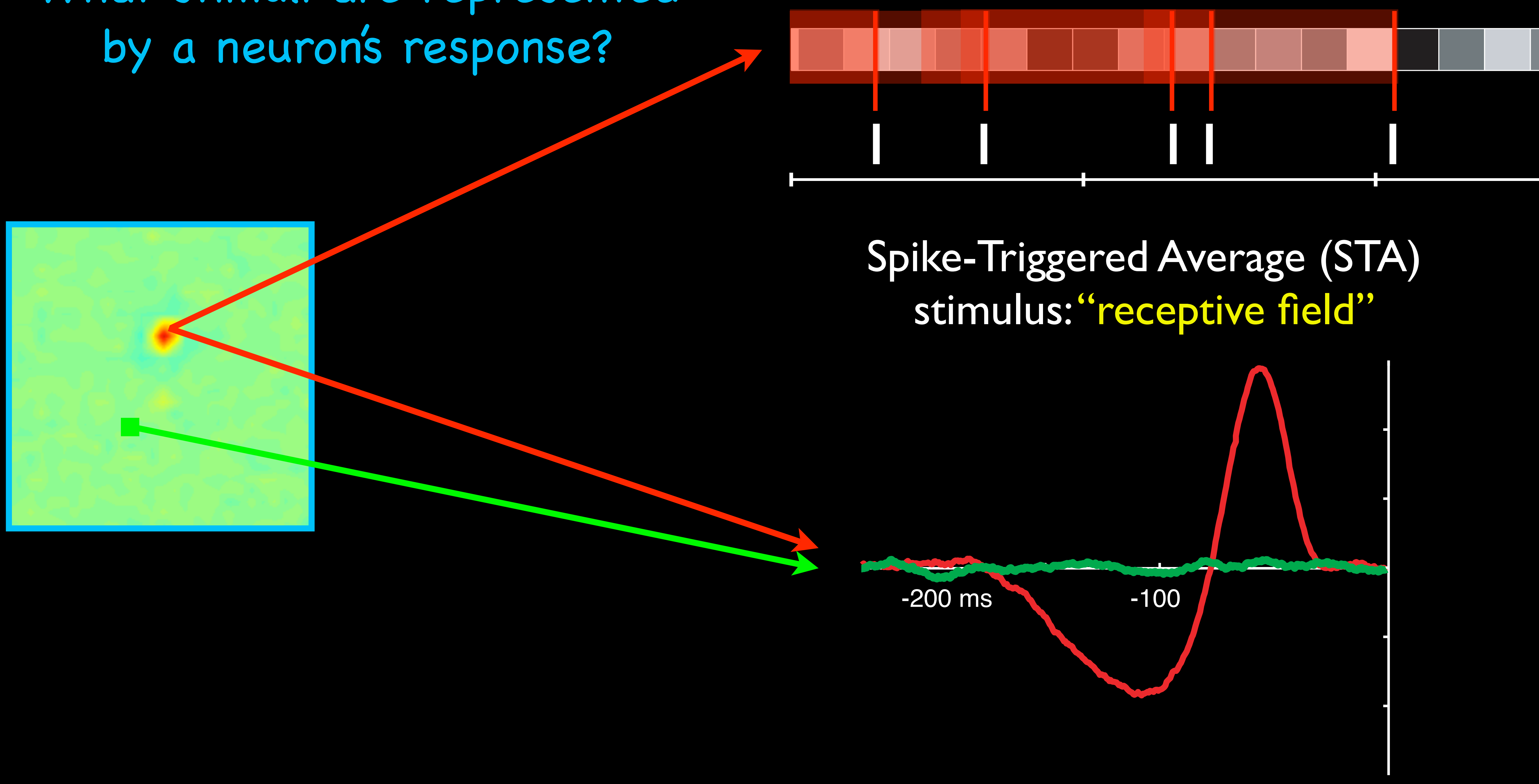
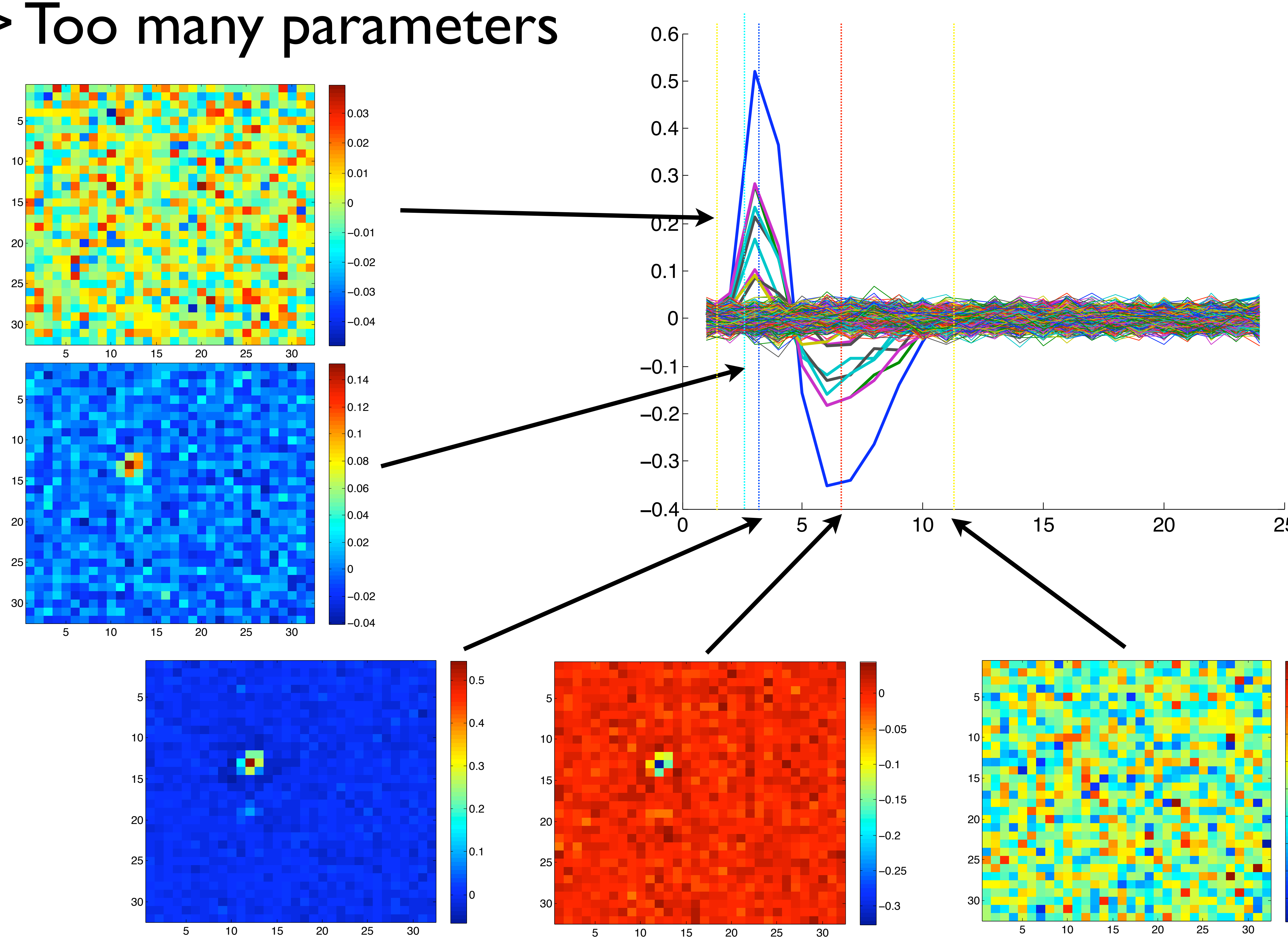


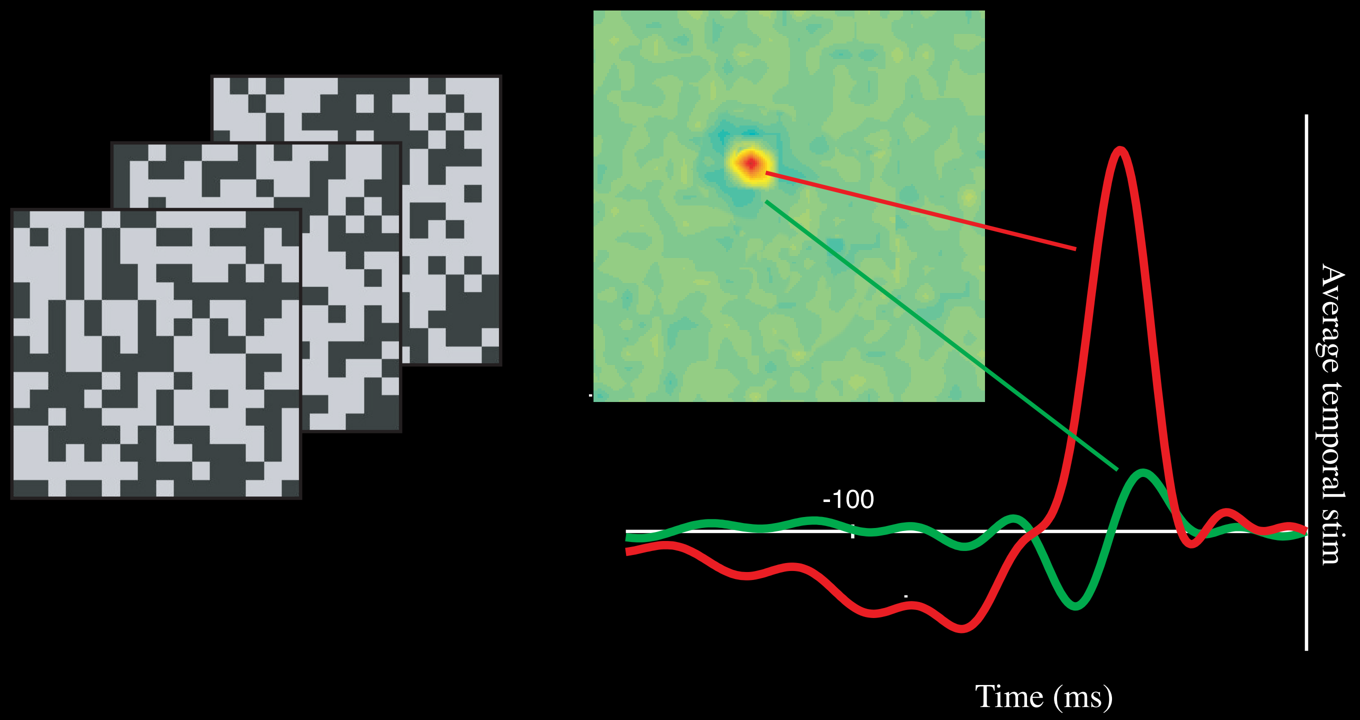
Implicit Problems with Modeling

> Too many parameters

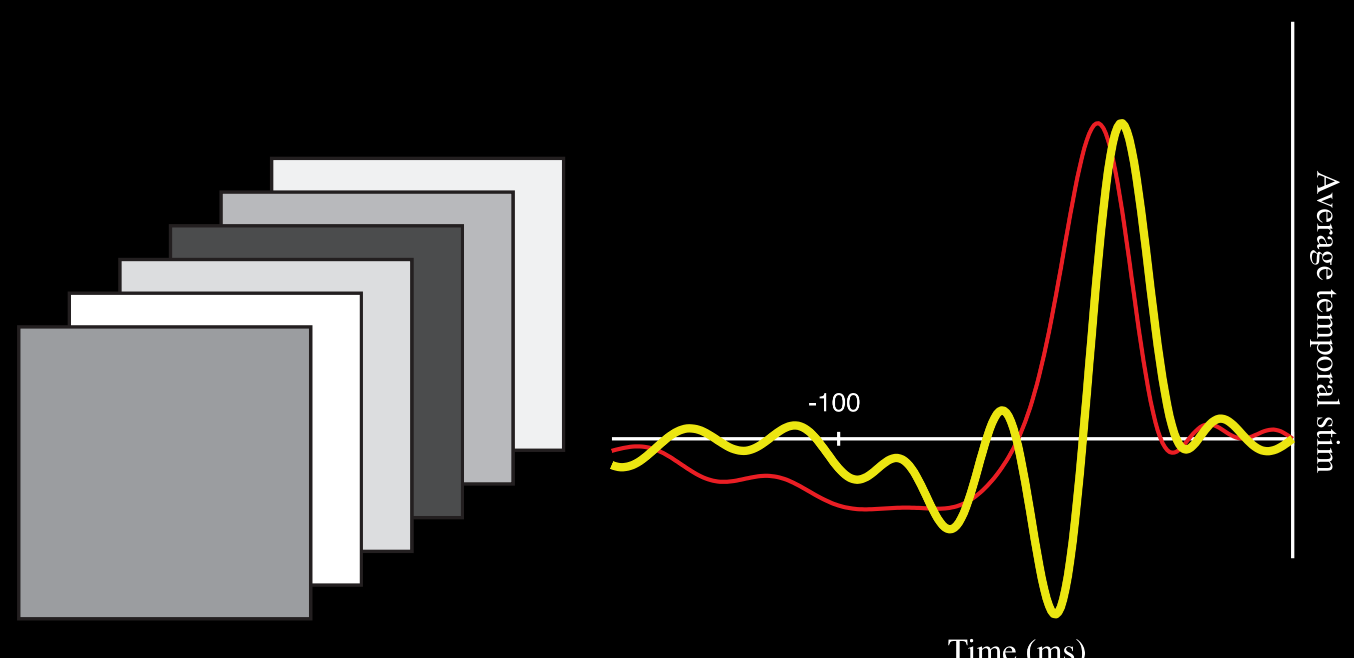


The "temporal receptive field"

Spatiotemporal Stimuli



Full-field stimuli



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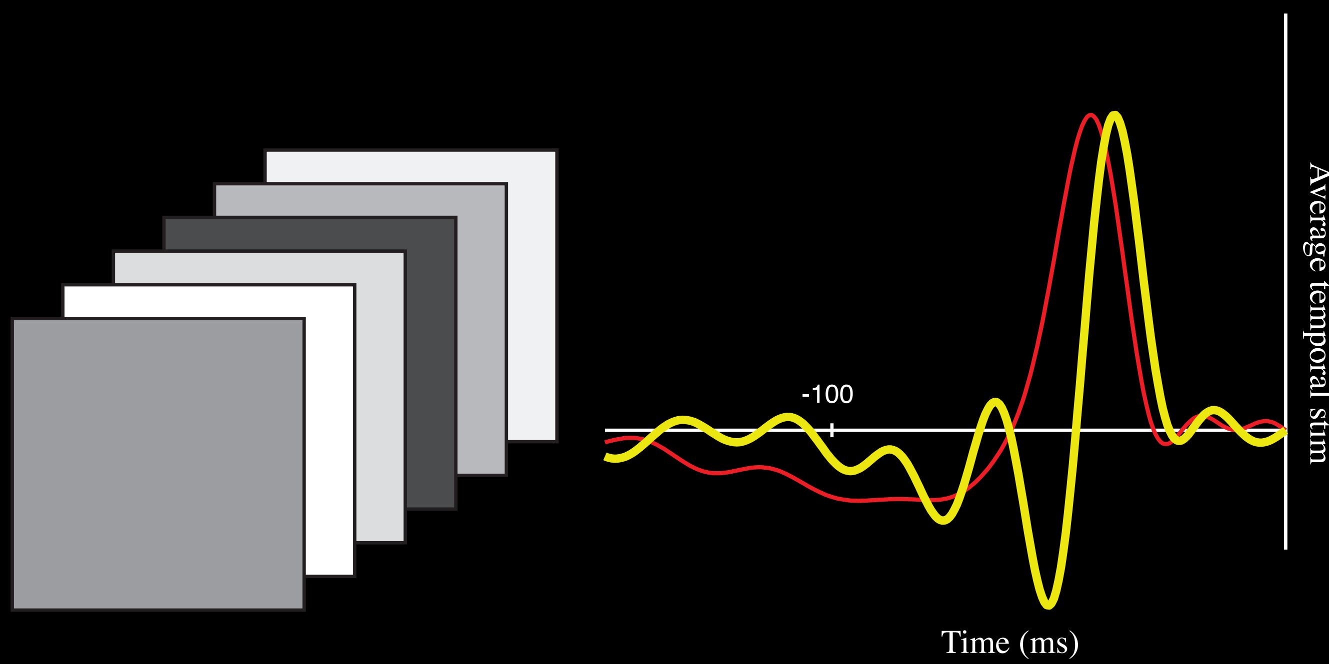
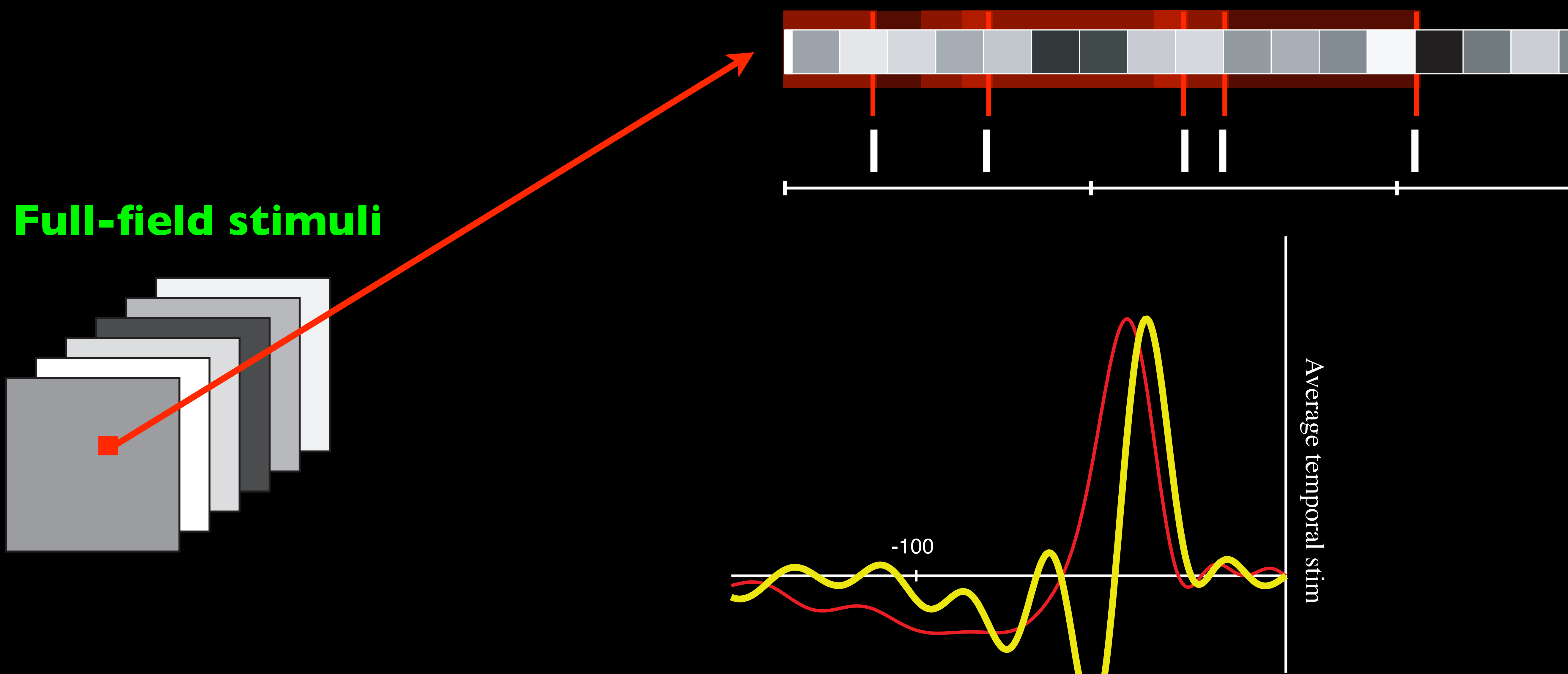
The "temporal receptive field"

Full-field stimuli



How measure the receptive field?
The spike-triggered average

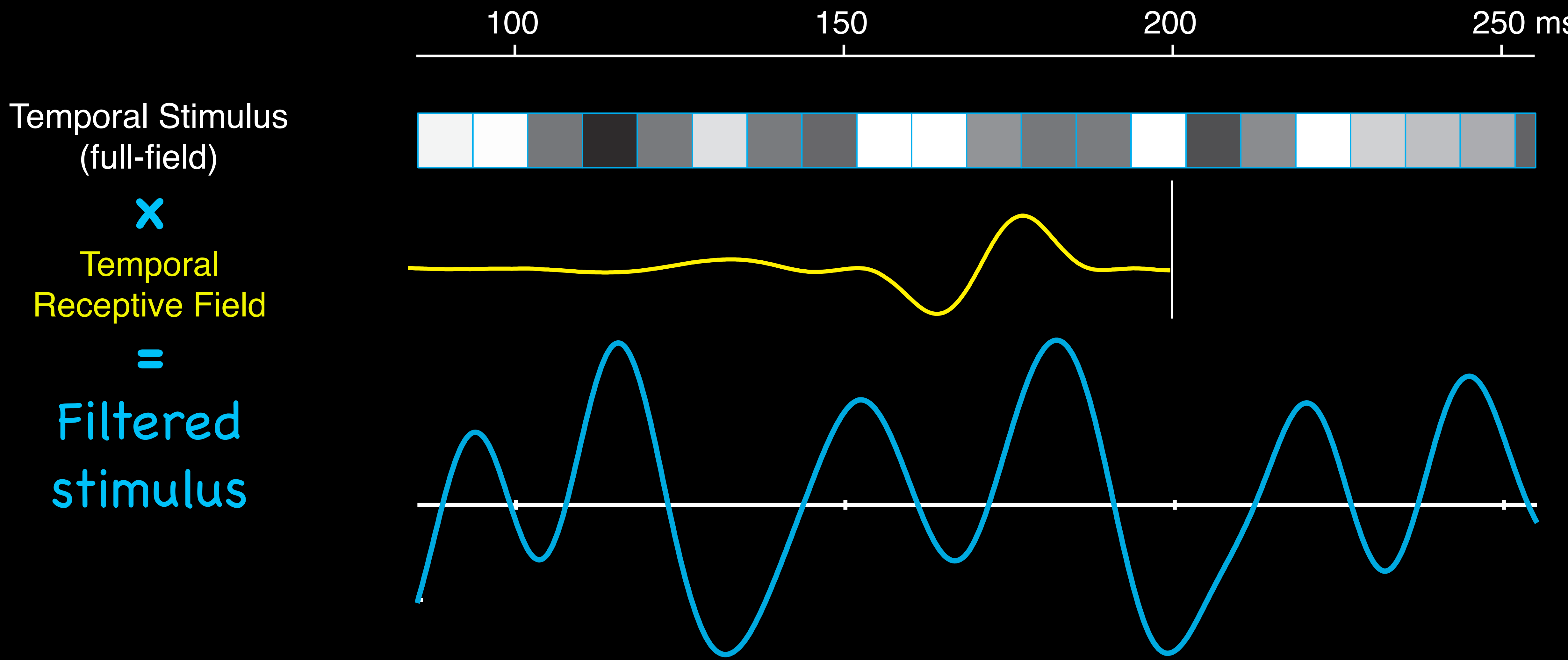
Full-field stimuli



Stimulus-response cross-correlation

$$k(\tau) \propto \int dt\; r(t)\, s(t-\tau)$$

Linear model predictions



$$r_{est}(t) = r_0 + \int d\tau\ k(\tau)\, s(t-\tau)$$

Mathematical result

(take functional derivative of MSE)

Layman's summary:
In the presence of Gaussian noise (uncorrelated) stimuli, the best linear model for the neuron is proportional to the spike triggered average.

$$r_{est}(t) = r_0 + \int d\tau \; k(\tau)\, s(t-\tau)$$

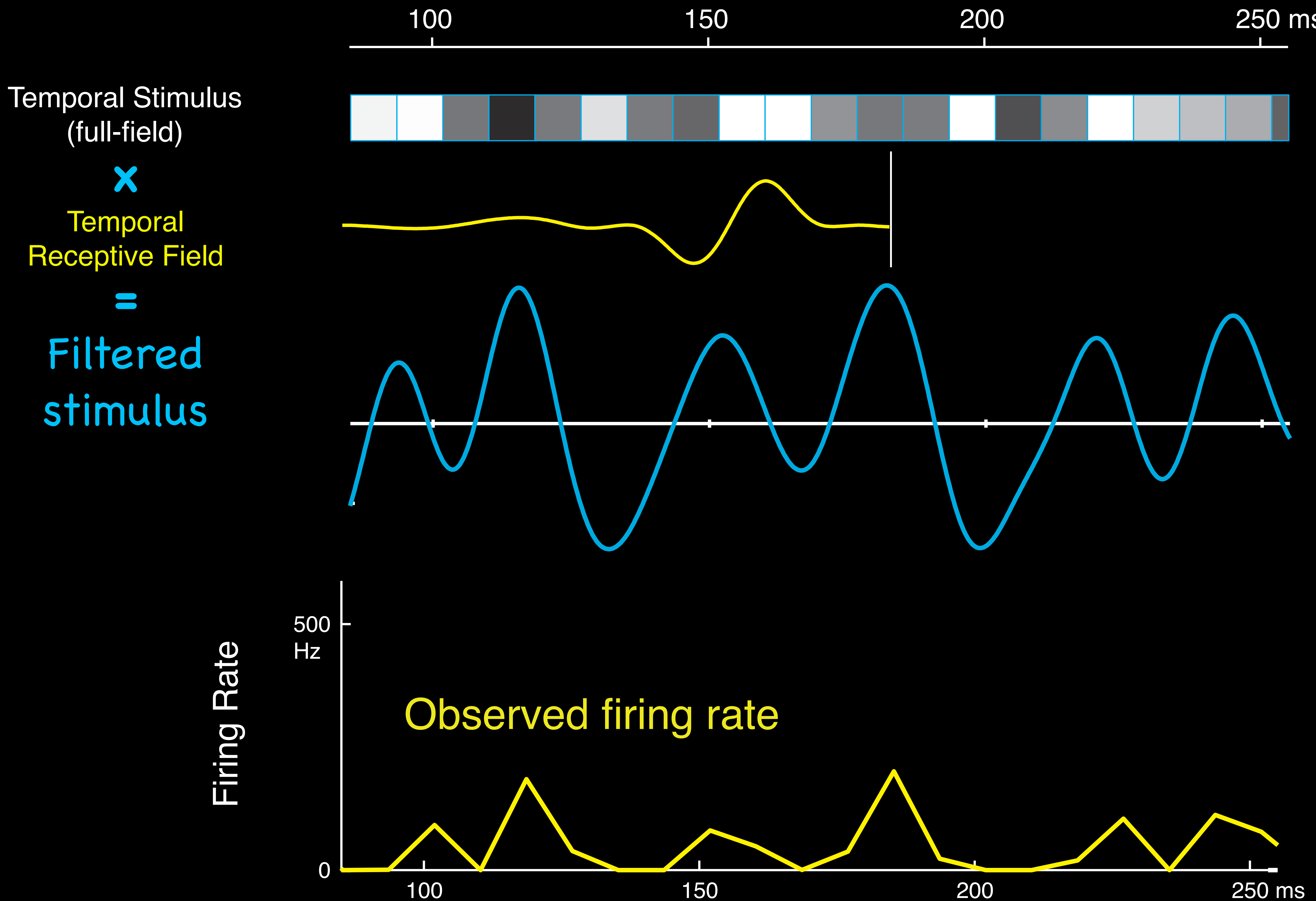
Mean Squared Error (MSE)

$$\mathrm{MSE} = \sum_t [r(t) - r_{est}(t)]^2$$

Stimulus-response cross-correlation

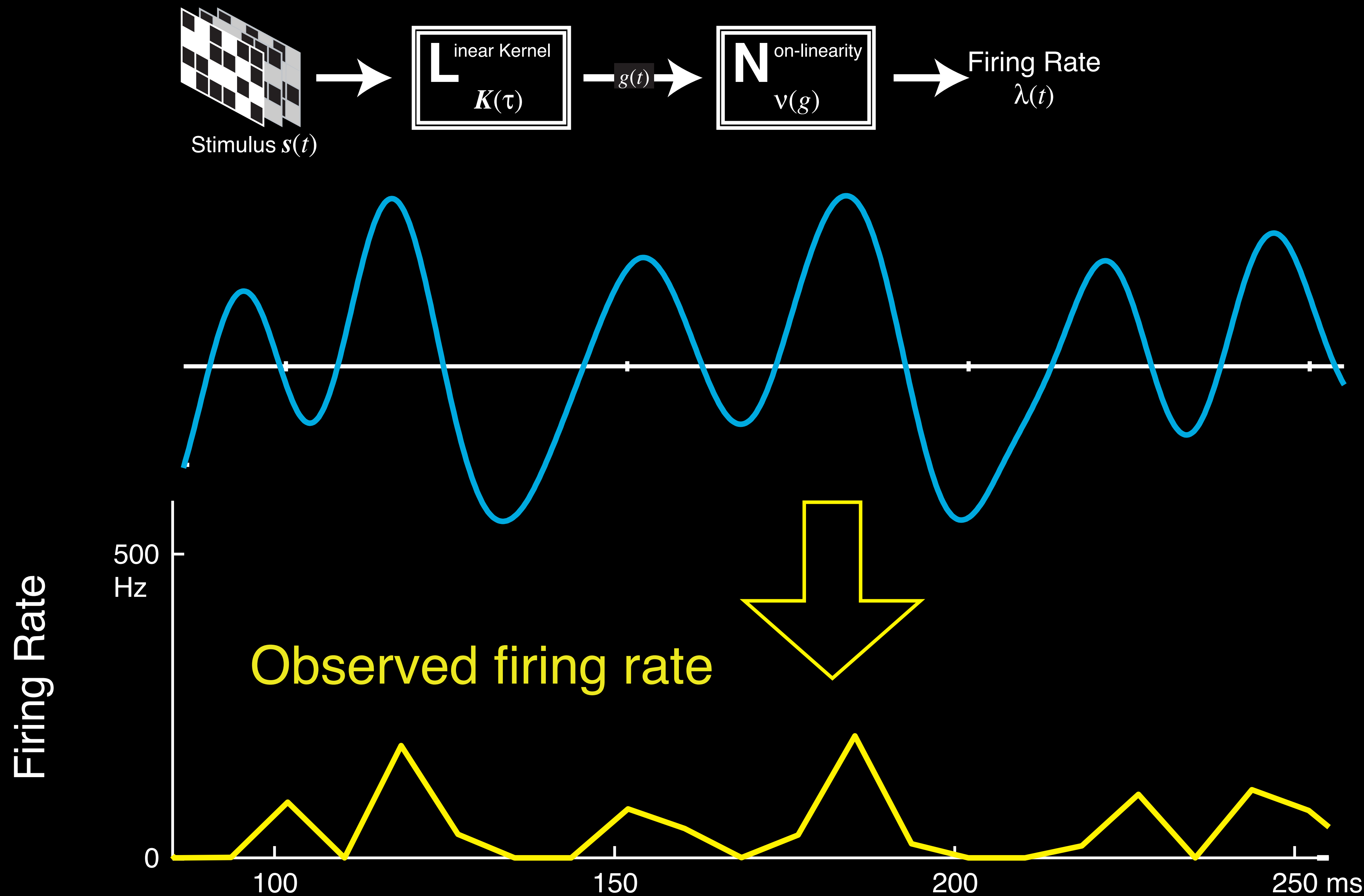
$$k(\tau) \propto \int dt \; r(t)\, s(t-\tau)$$

Linear model predictions

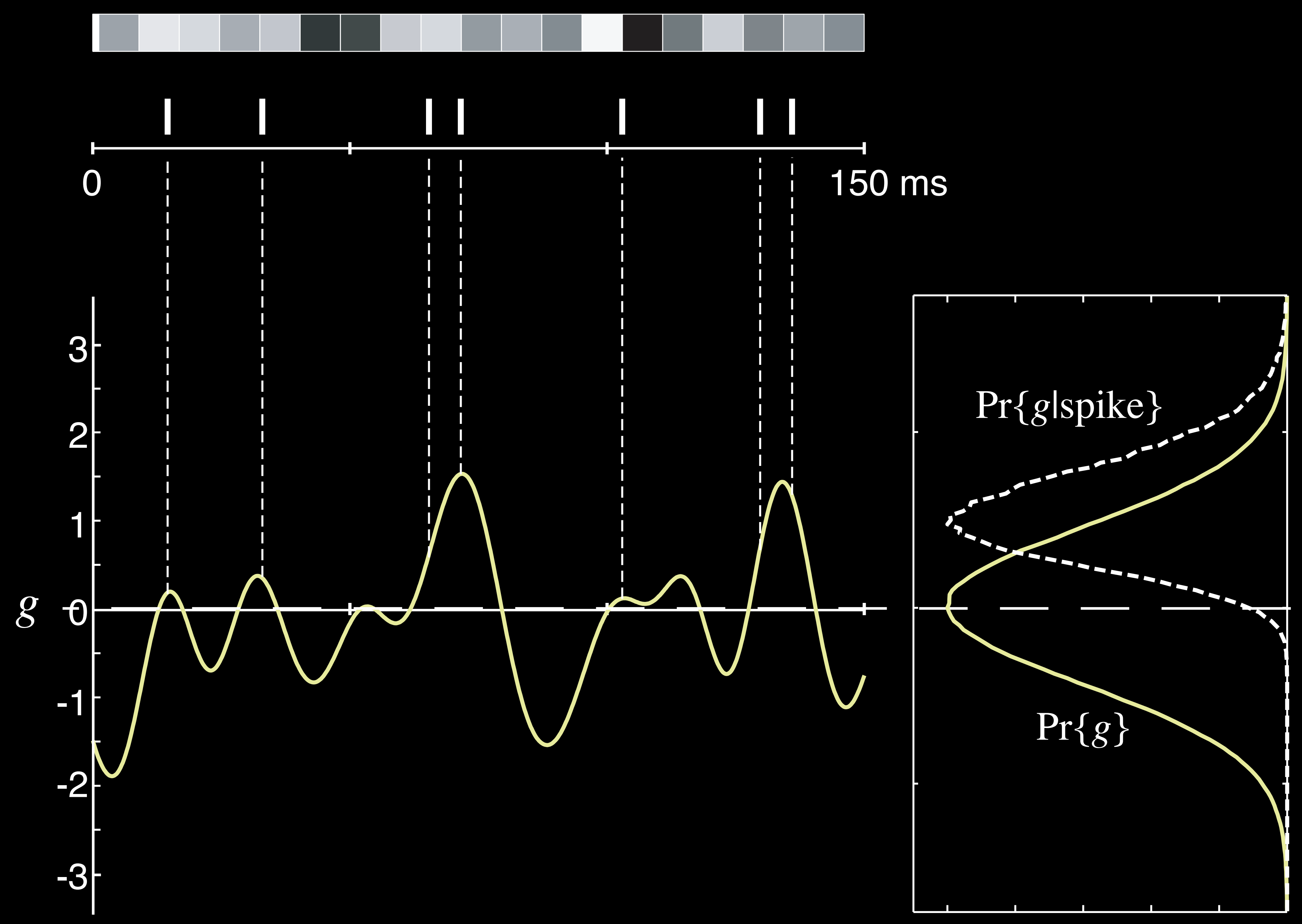


How map linear function to firing rate?

"LN" (Linear-Non-Linear) model of encoding



Measuring reliability of RF "model": the non-linearity



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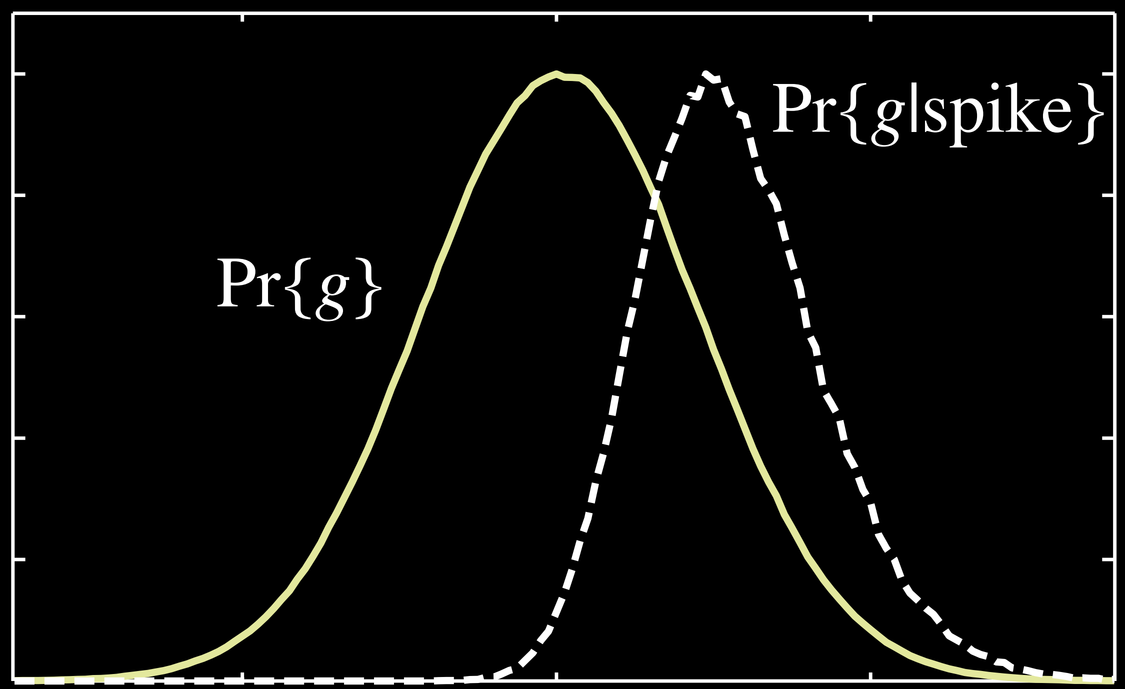
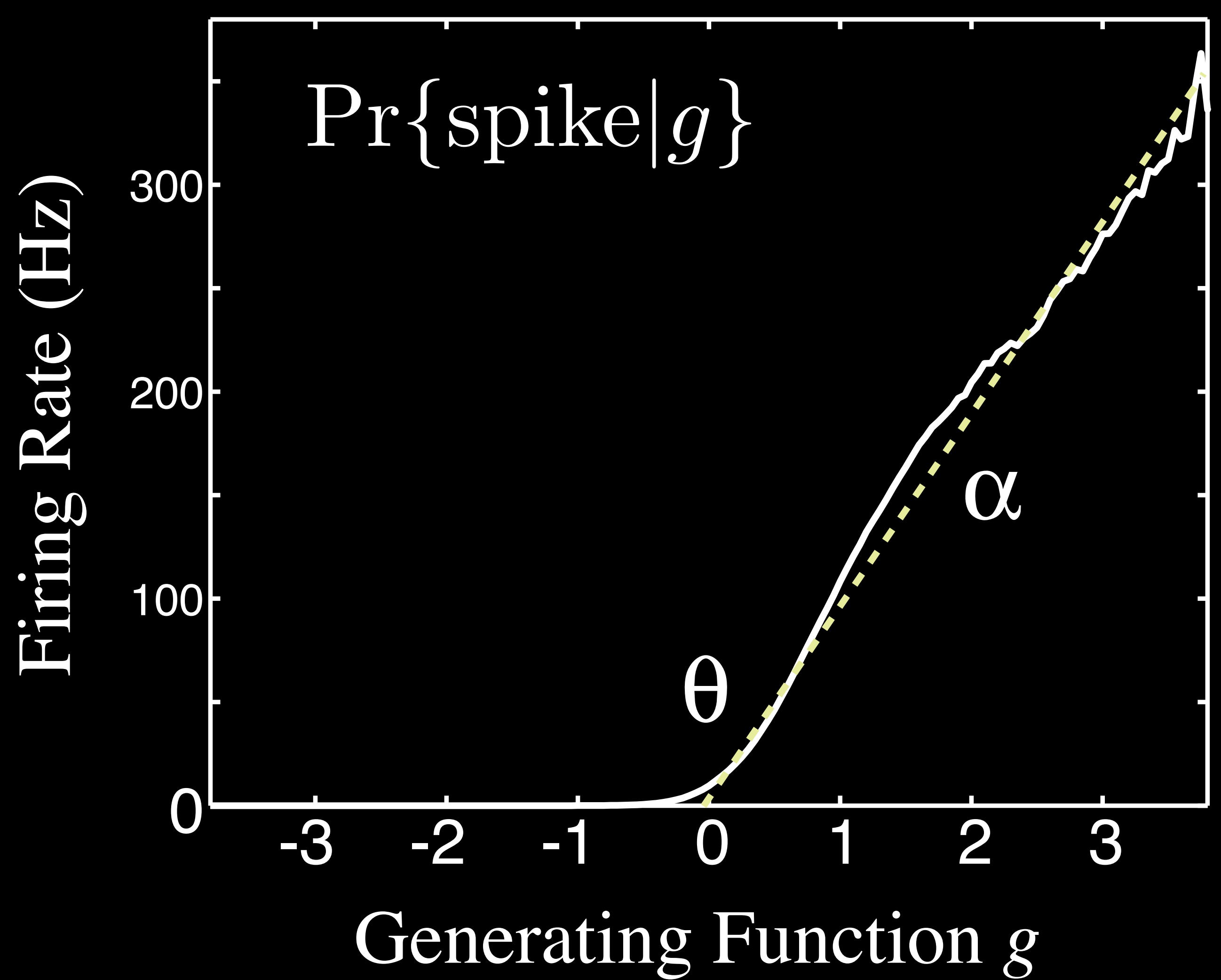
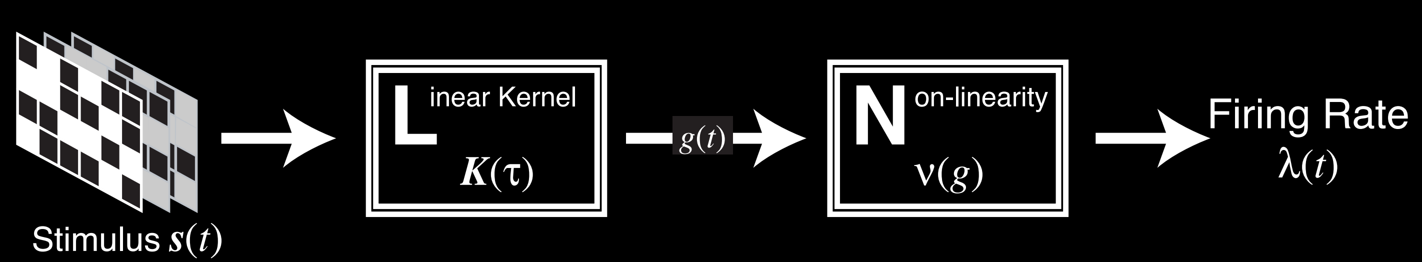




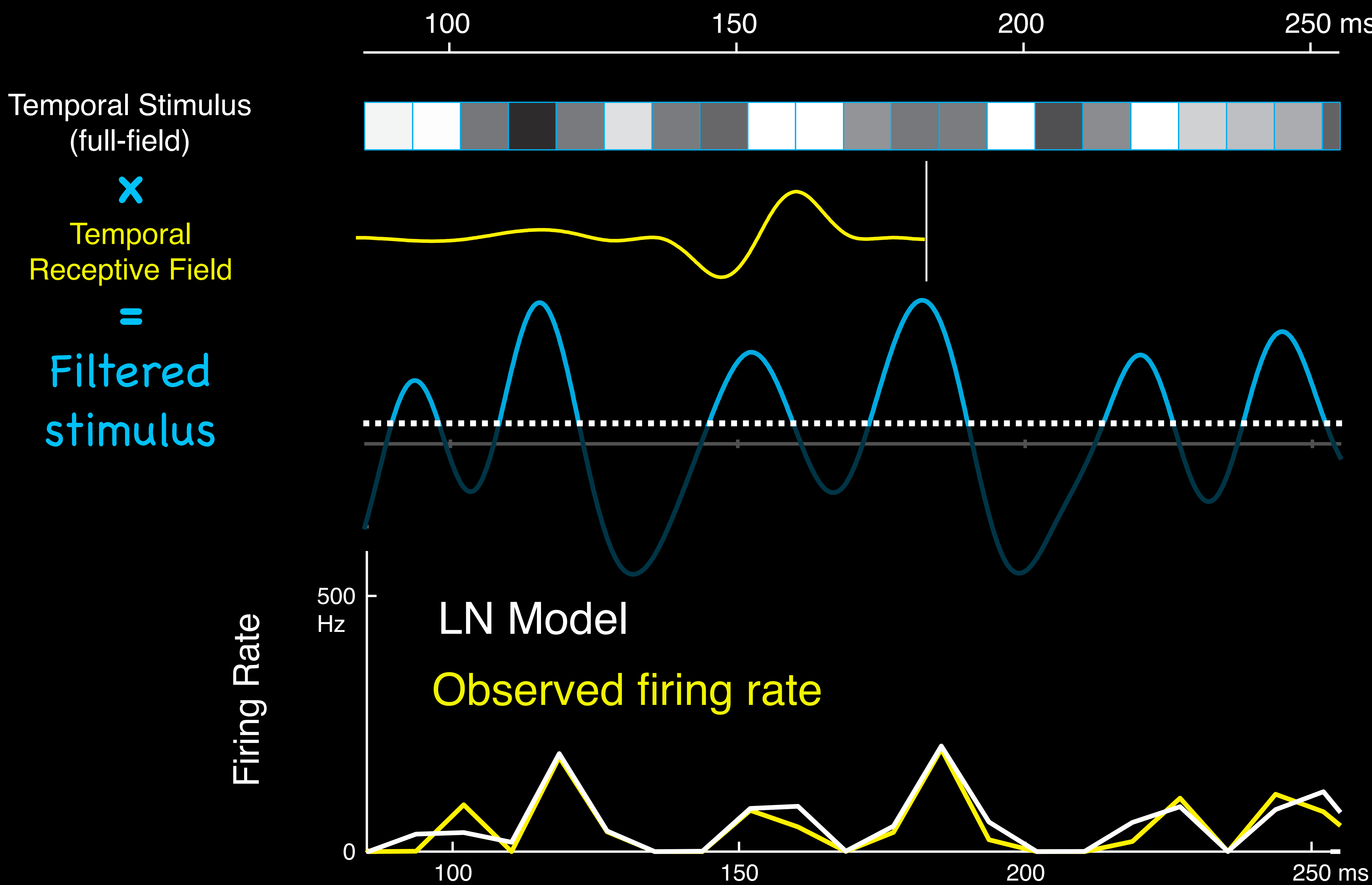
LN Model of Encoding



Bussgang's Theorem

Layman's summary:
In the context of simple non-linearities, the "optimal" receptive field is STIL given by the spike-triggered average in the context of Gaussian white noise ***

Receptive field predictions



How quantify quality of model fit?

Matlab Interlude

Problems with visual neuron modeling

1. Looking at higher time resolution reveals that the LN model is insufficient

2. Non-linearities “force” the use of Bussgang’s theorem -> only use STA, and need noise stimuli

3. r2 is not the best measure for evaluating a non-linear system

(also, it requires multiple repeats to estimate a good firing rate)

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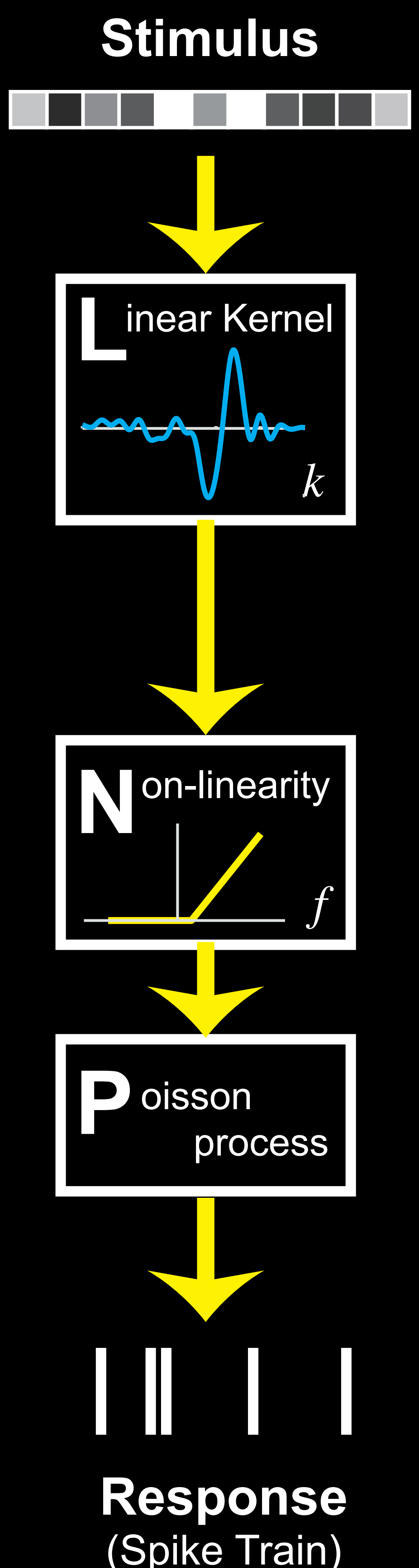
Maximum Likelihood Approach



Likelihood: probability that model explains data

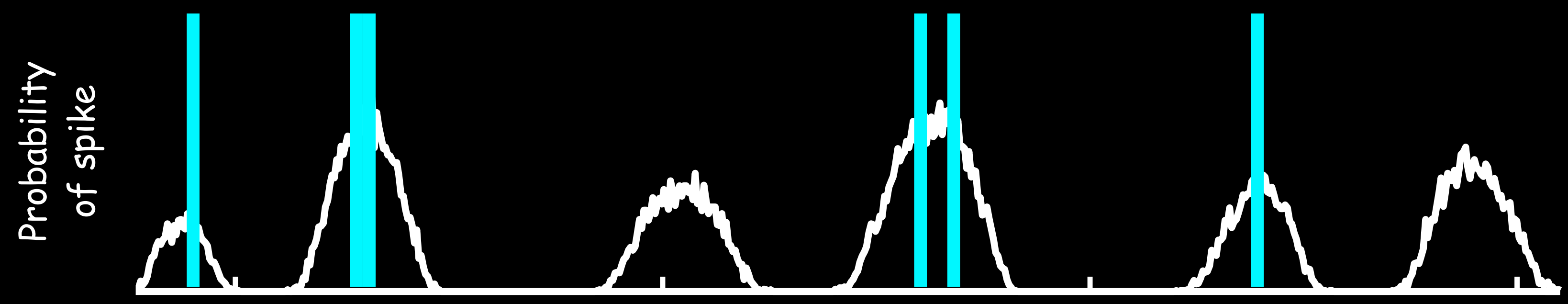
Find the "maximum likelihood":

The probability that the spikes were generated by a model with a certain choice of parameters

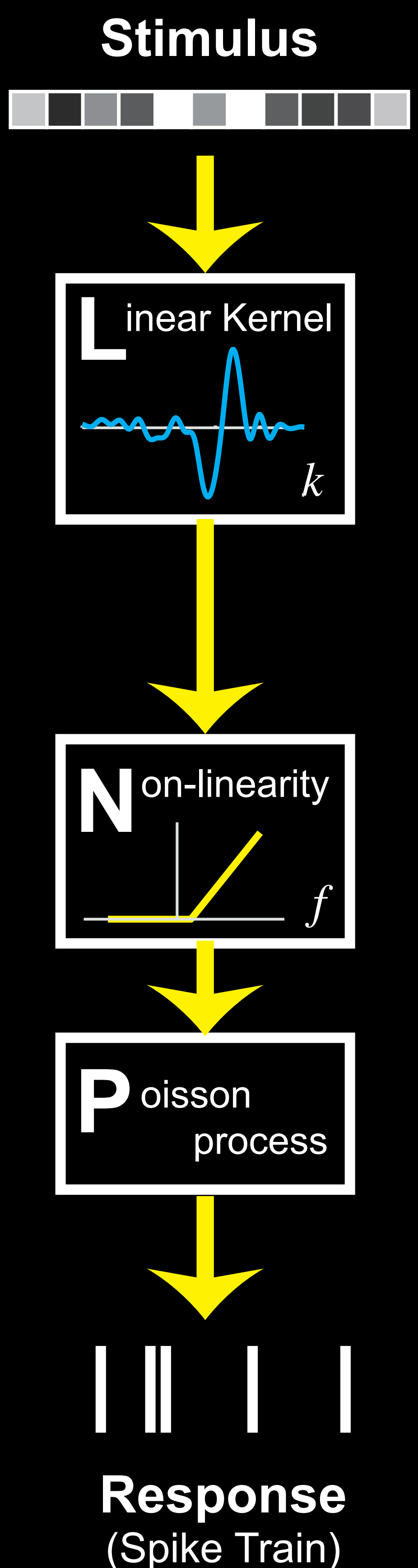
$$\mathrm{LL} = \sum_{t_{spk}} \log Pr\{\mathrm{spk}|t_{spk}\} - \sum_{t} Pr\{\mathrm{spk}|t\}$$

Firing rate when there is an observed spike

Firing rate when there is no observed spike



Problem: complicated function to maximize!



The maximum likelihood:

$$\mathrm{LL} = \sum_{t_{spk}} \log Pr\{\mathrm{spk}|t_{spk}\} - \sum_{t} Pr\{\mathrm{spk}|t\}$$

Paninski (2004):

No local minima in likelihood surface given certain forms of non-linearity (f)

Matlab can solve for optimal parameters in very little time!

[e.g., 2 minutes of data, 0.5 ms resolution
~ 20 seconds]

LN model is fit “optimally” using maximum likelihood

Quick Matlab Interlude

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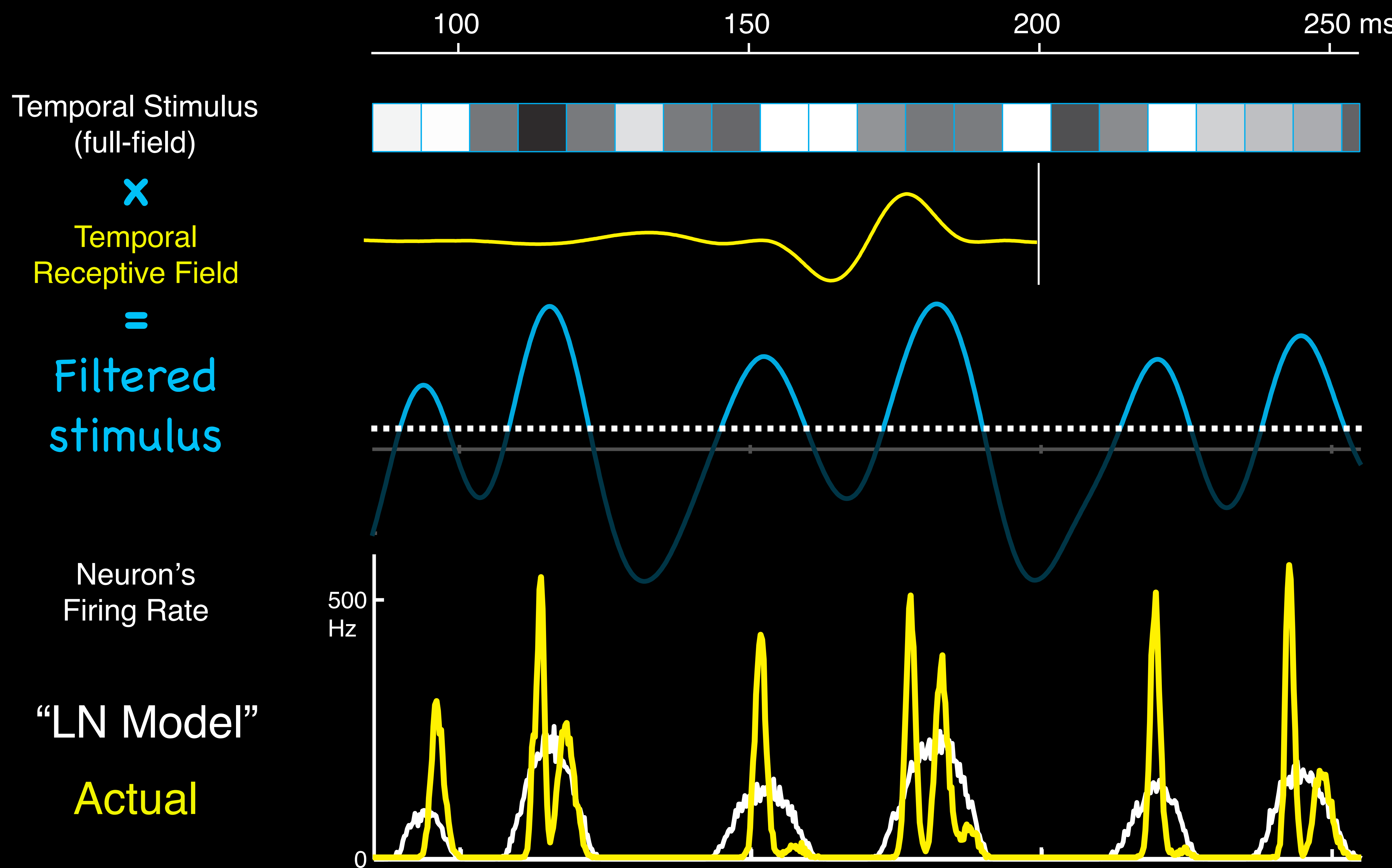
Receptive field predictions



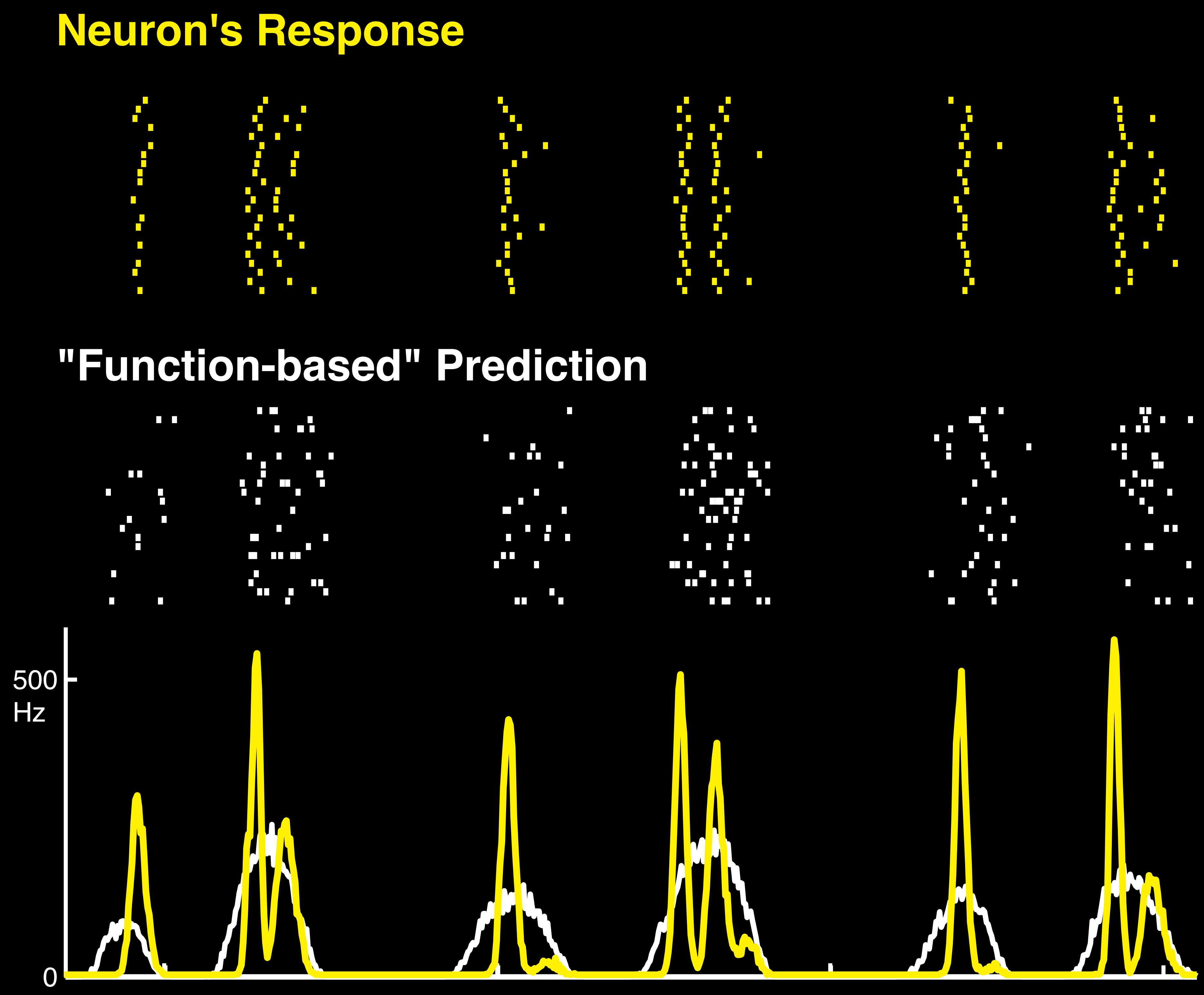
Receptive field predictions

Spike Rasters

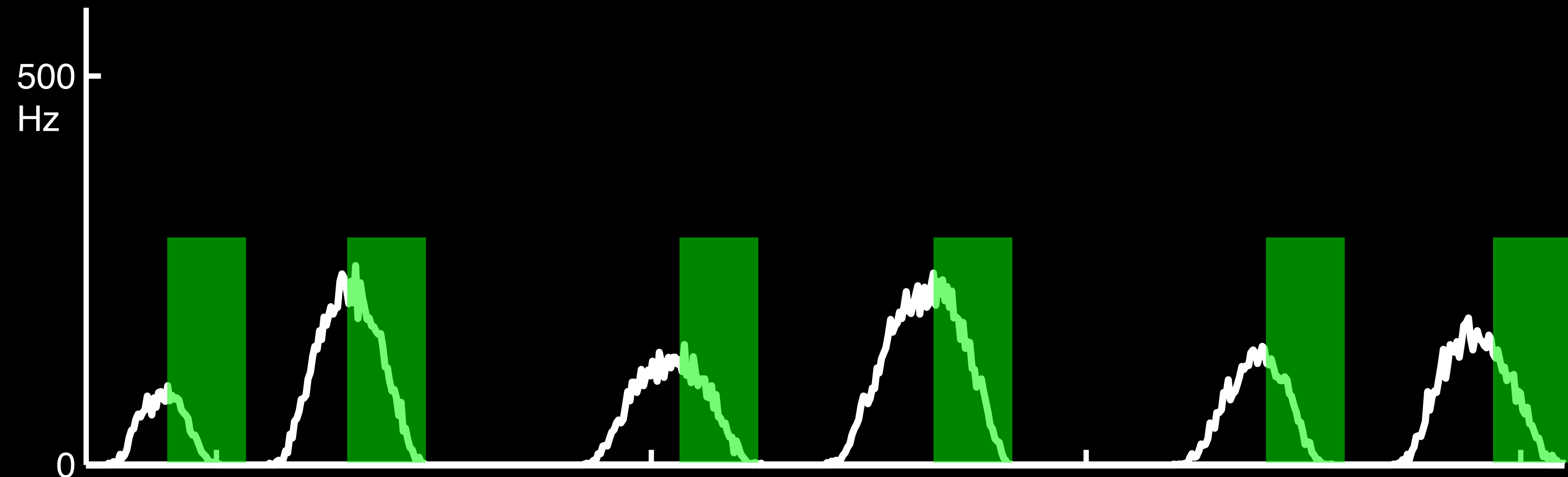
Neuron's Firing Rate

"LN Model"

Actual



How to generate precision?

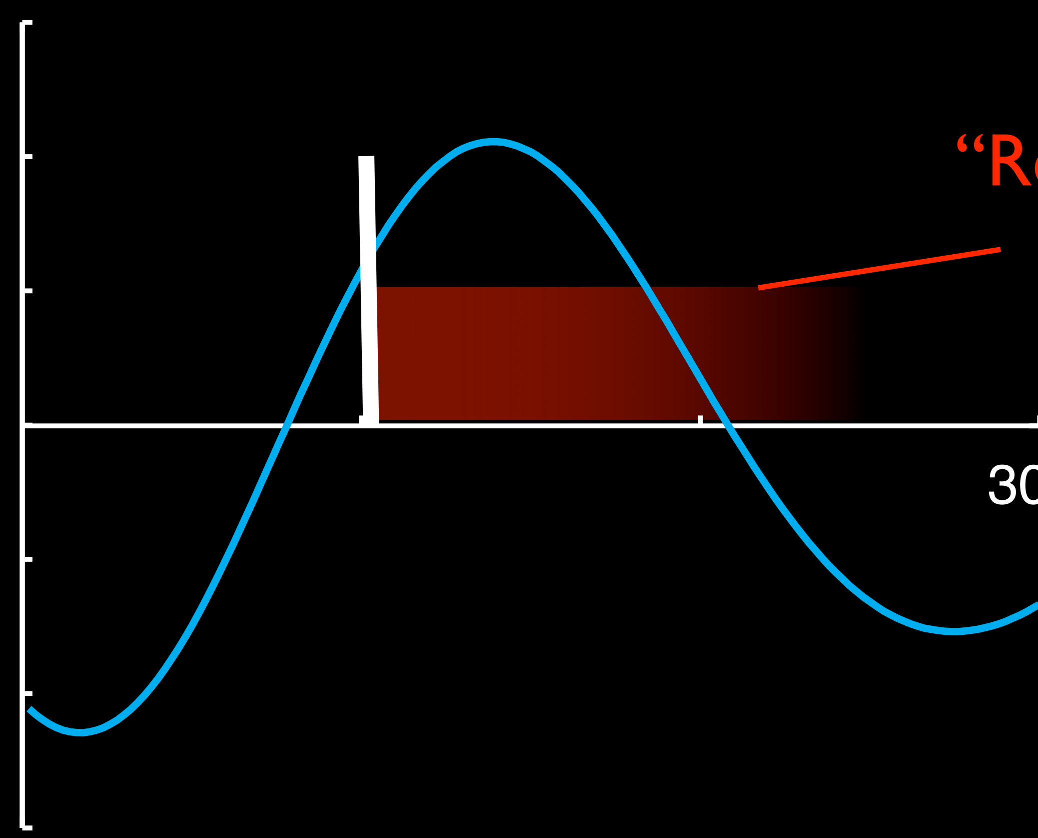


Neuron is "tuned" to the stimulus

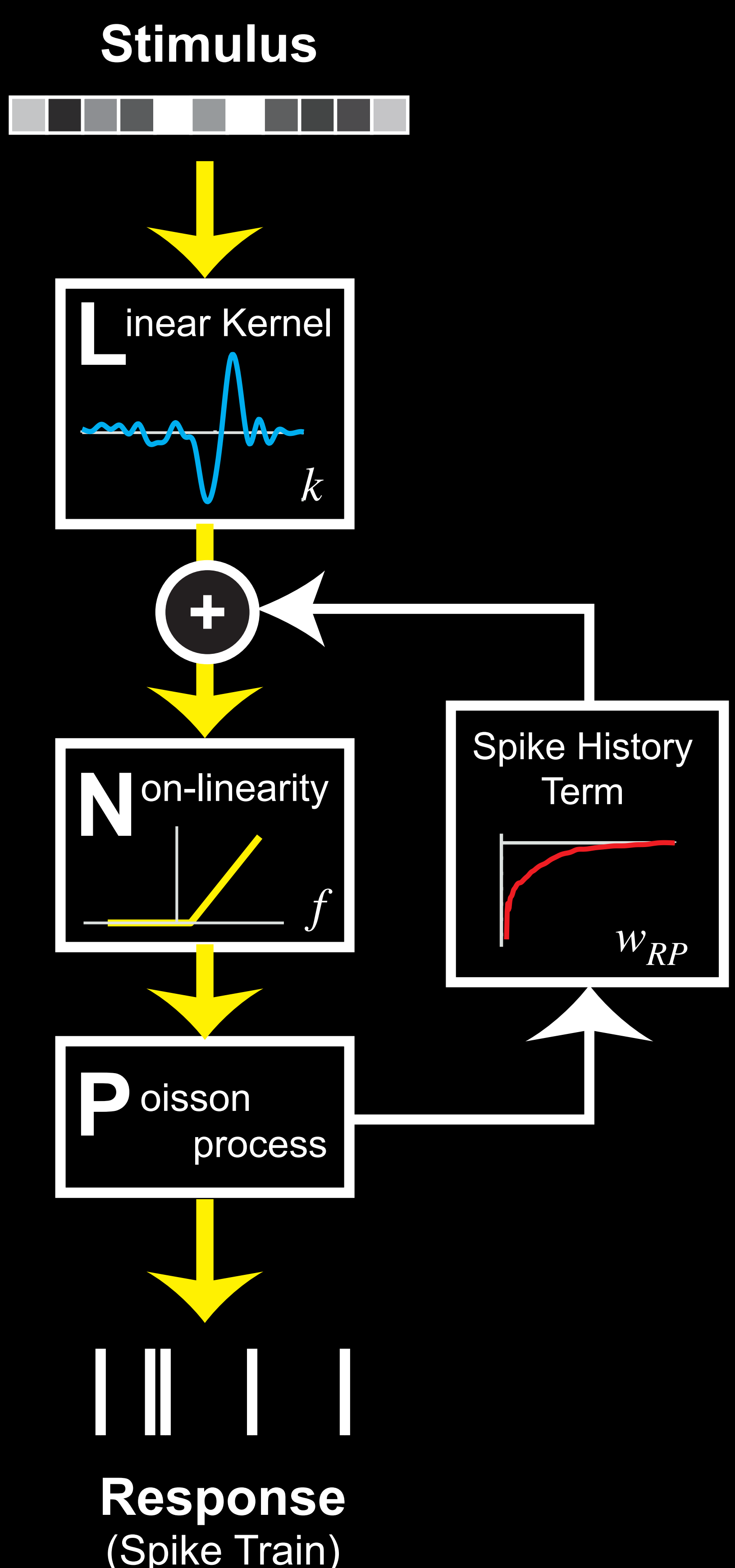
Need to "suppress" neuron's response during periods of stimulus that matches RF

Refractoriness and Neural Precision

e.g., Berry and Meister, 1998
Brillinger, 1992
Keat et al., 2001
Paninski, 2004
Pillow et al., 2005
...



Generalized Linear Model (GLM)

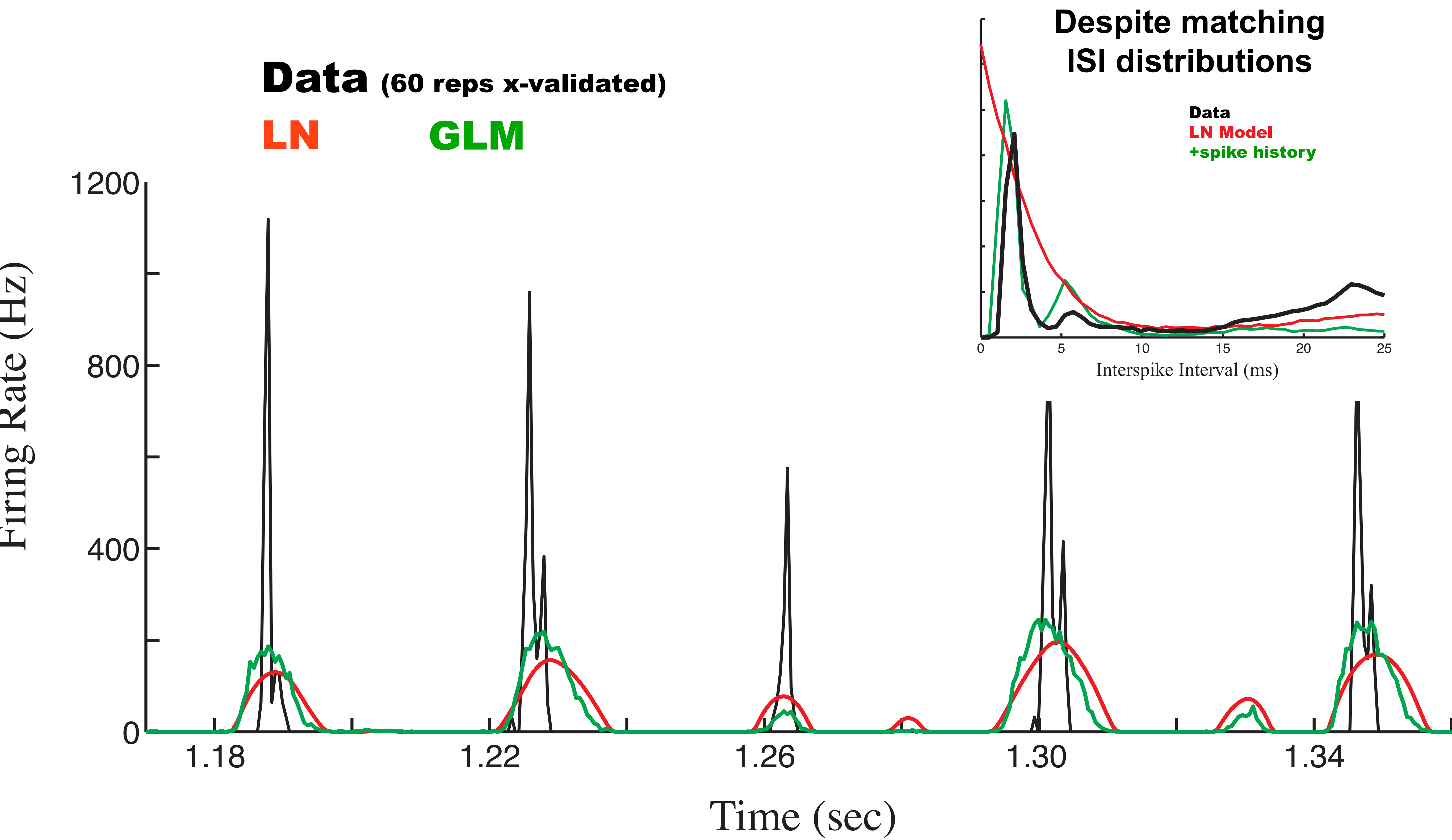


Paninski (2004):

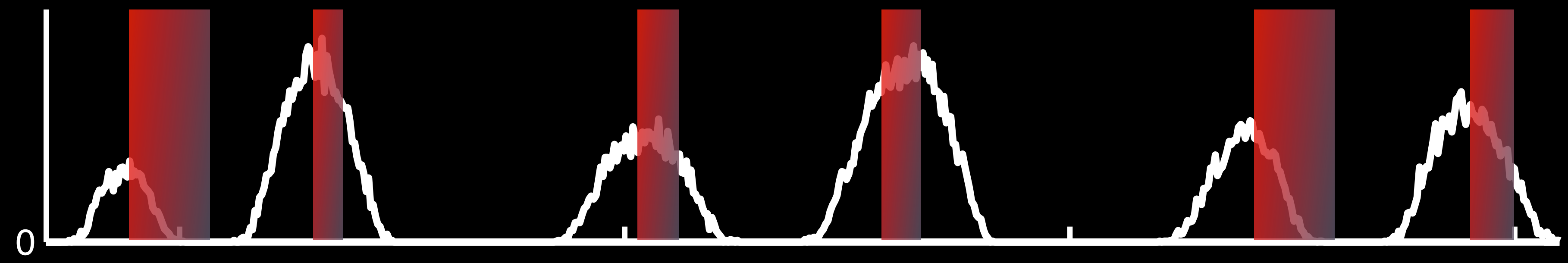
Optimal solution for model parameters
(no matter how many parameters!)

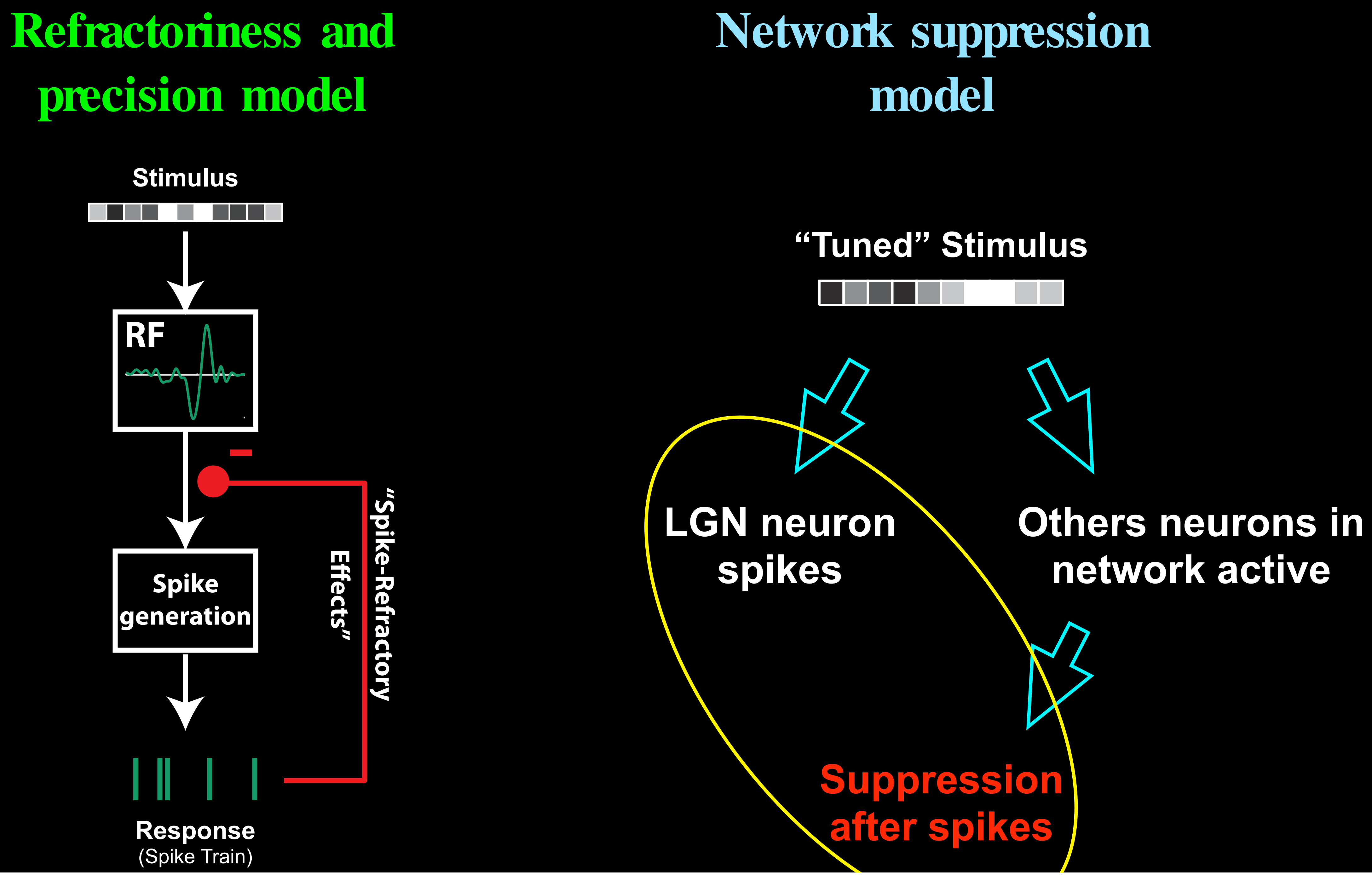
But, spike history term does not explain the temporal resolution of the data.

GLM model does not explain LGN temporal precision



What about "network" suppression?





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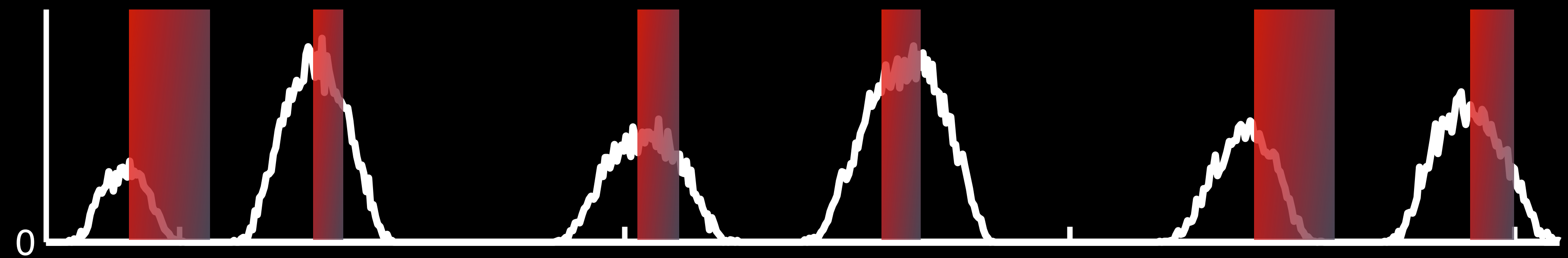
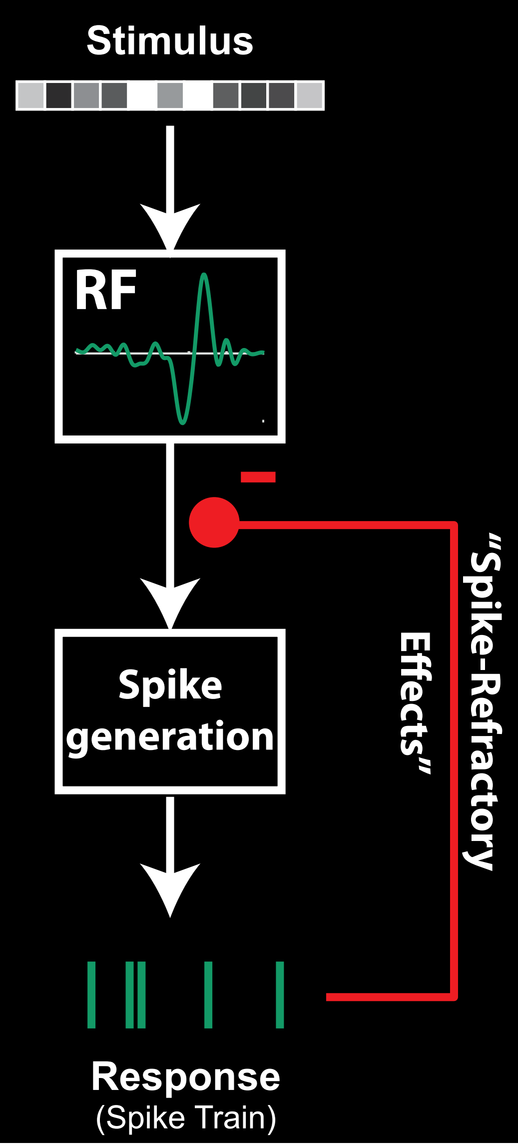
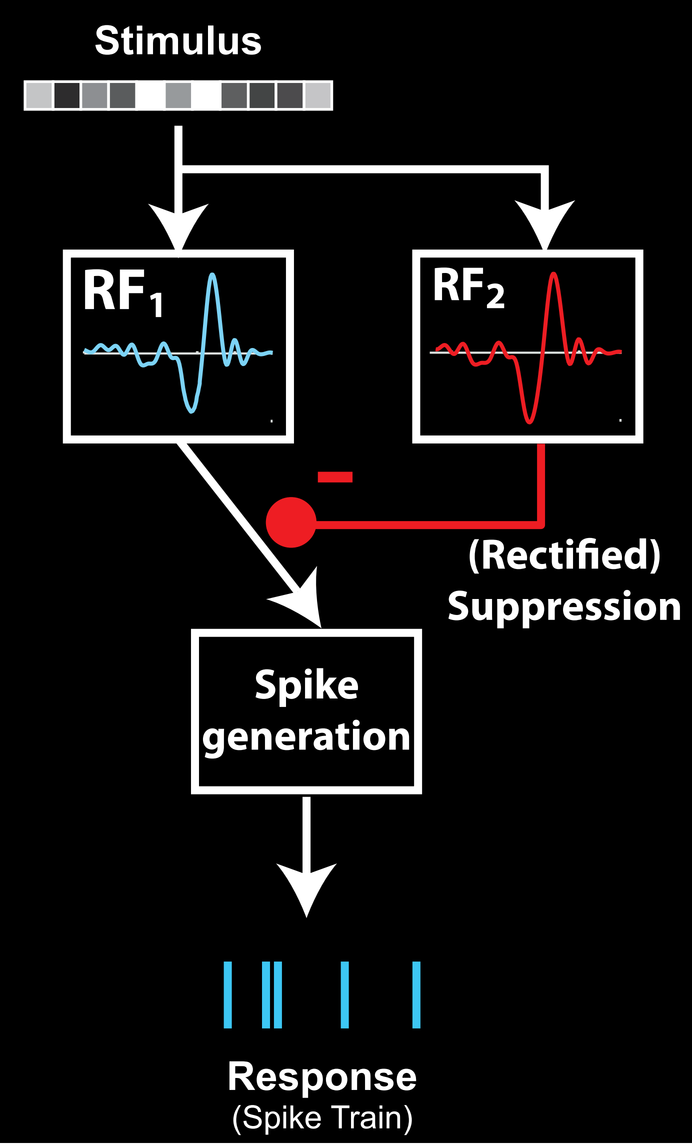


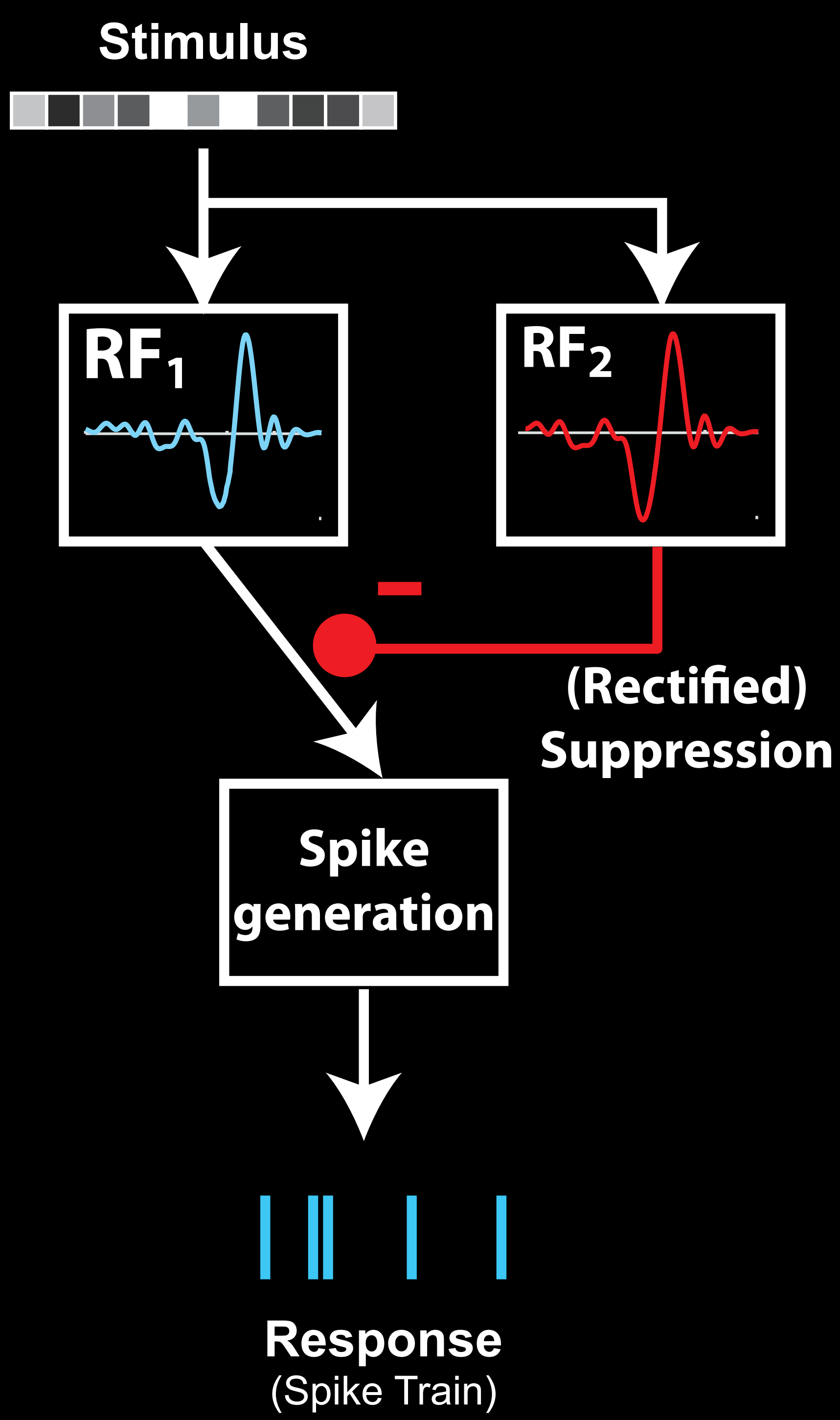
Refractoriness and precision model



Network suppression model



Directly fit *multiple* receptive fields

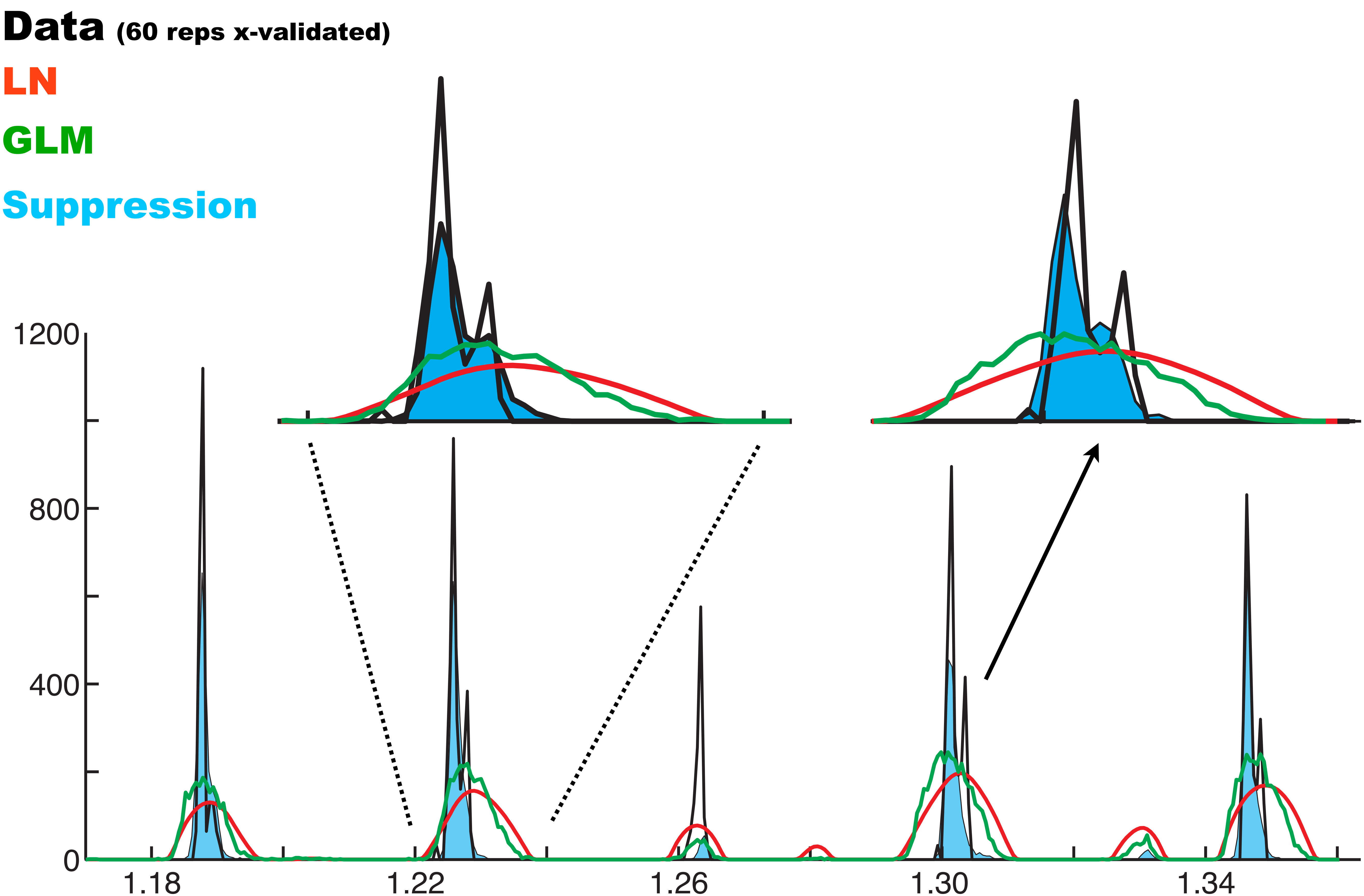


-- Alternative to spike-triggered covariance

-- Simplest way to incorporate two RFs

-- Application to neurons that process stimuli non-linearly (e.g., on-off cells in mouse retina)

“Precision” explained by suppression



Cross-validation

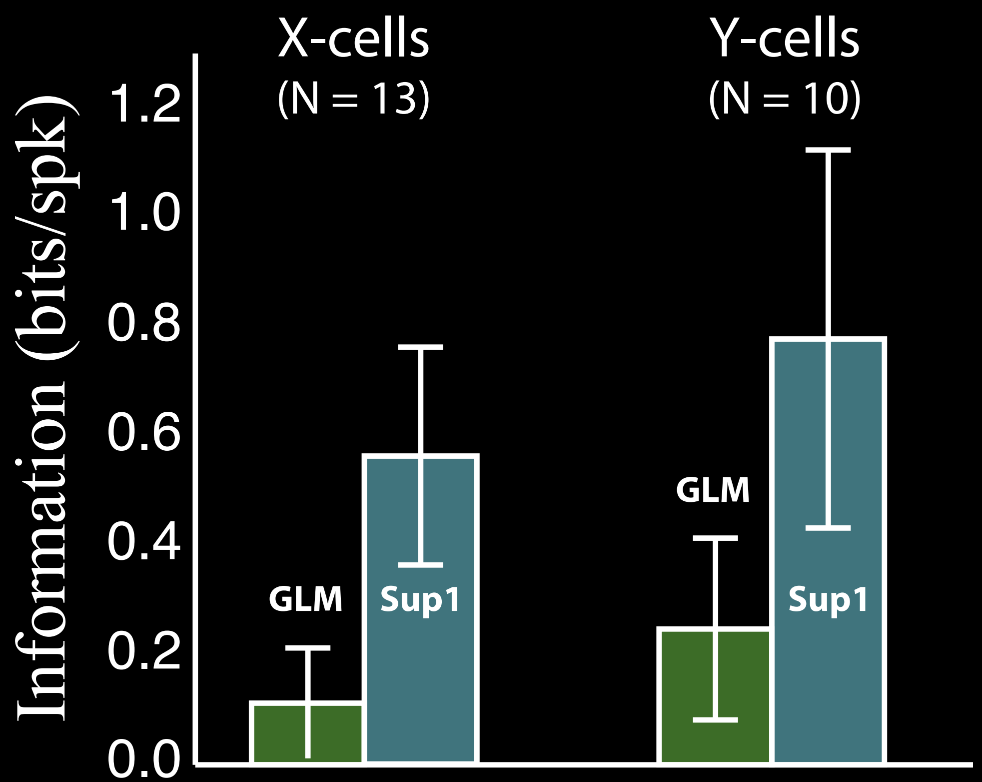
Fit model to 2 min

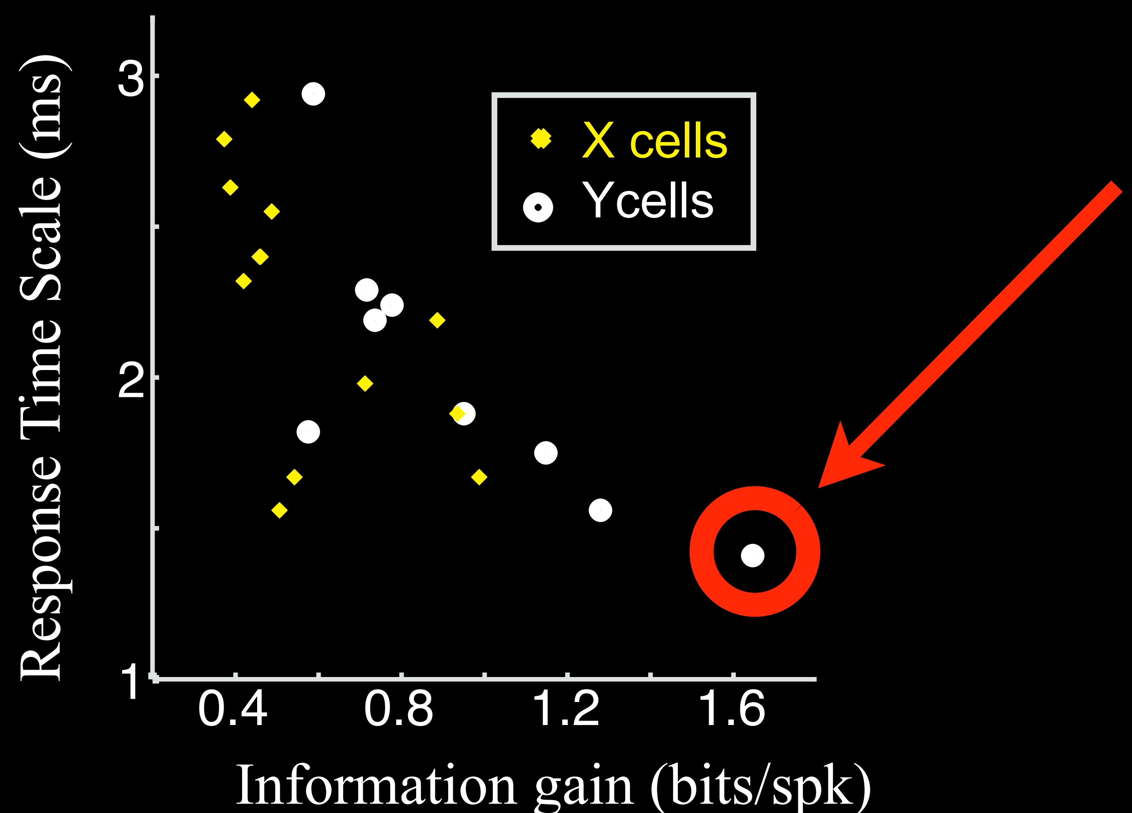
2 minutes of FF stimulation

Model test

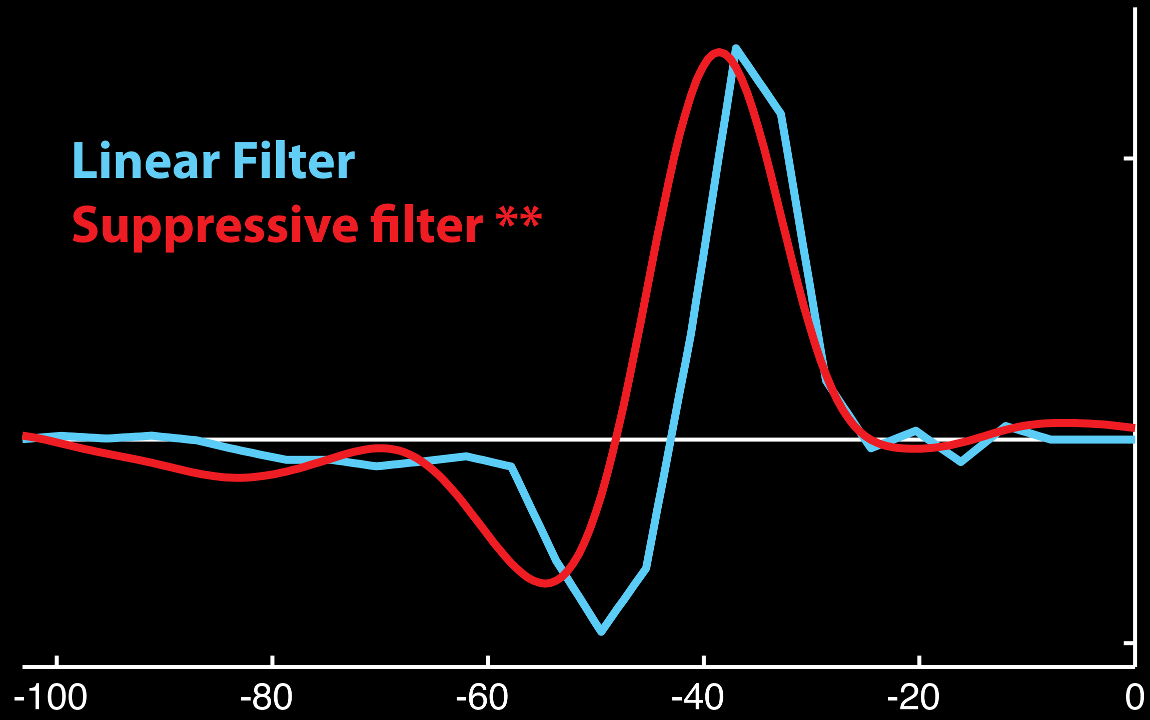
30 sec unique sequence repeated 60 times

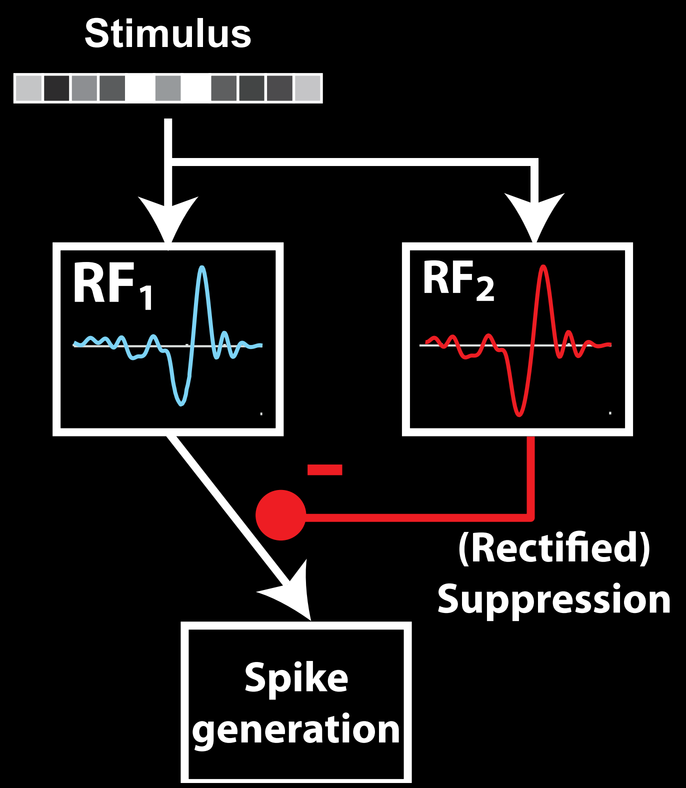
Significant improvement across all recorded neurons

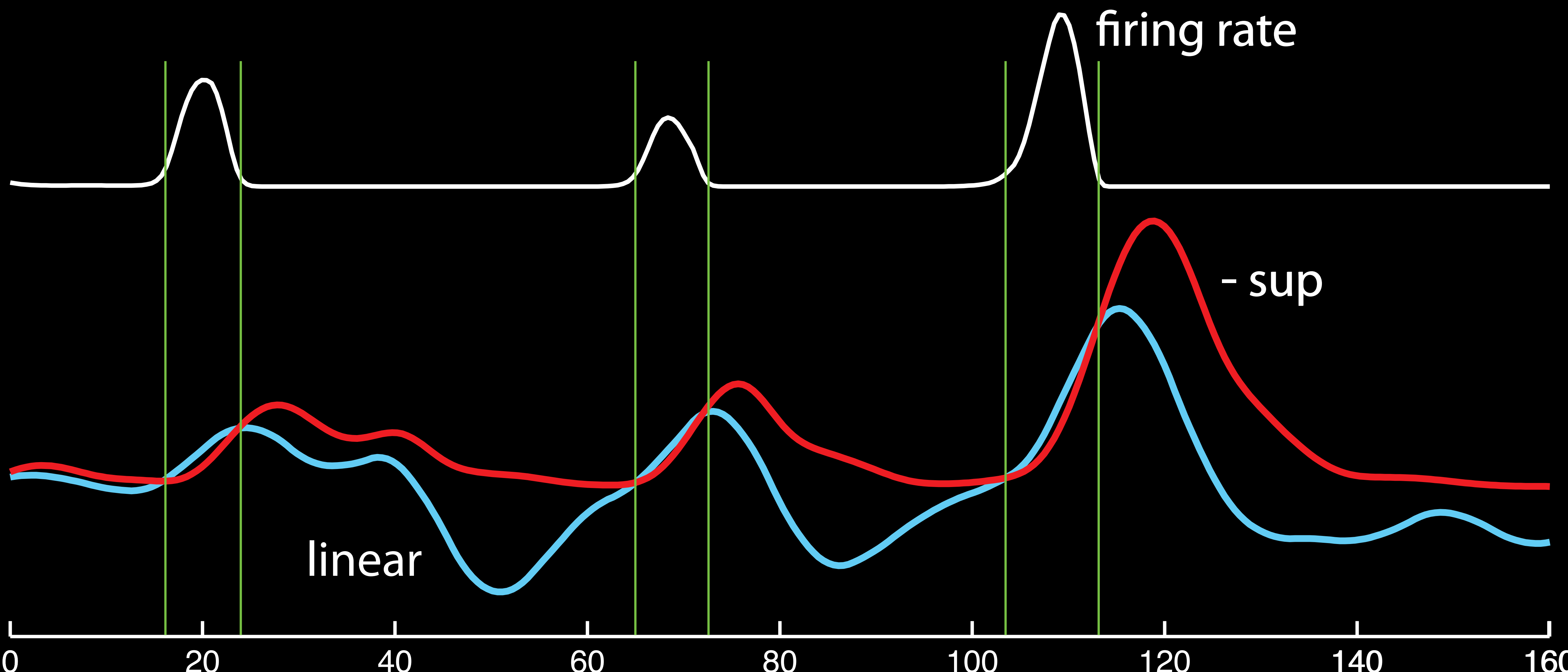




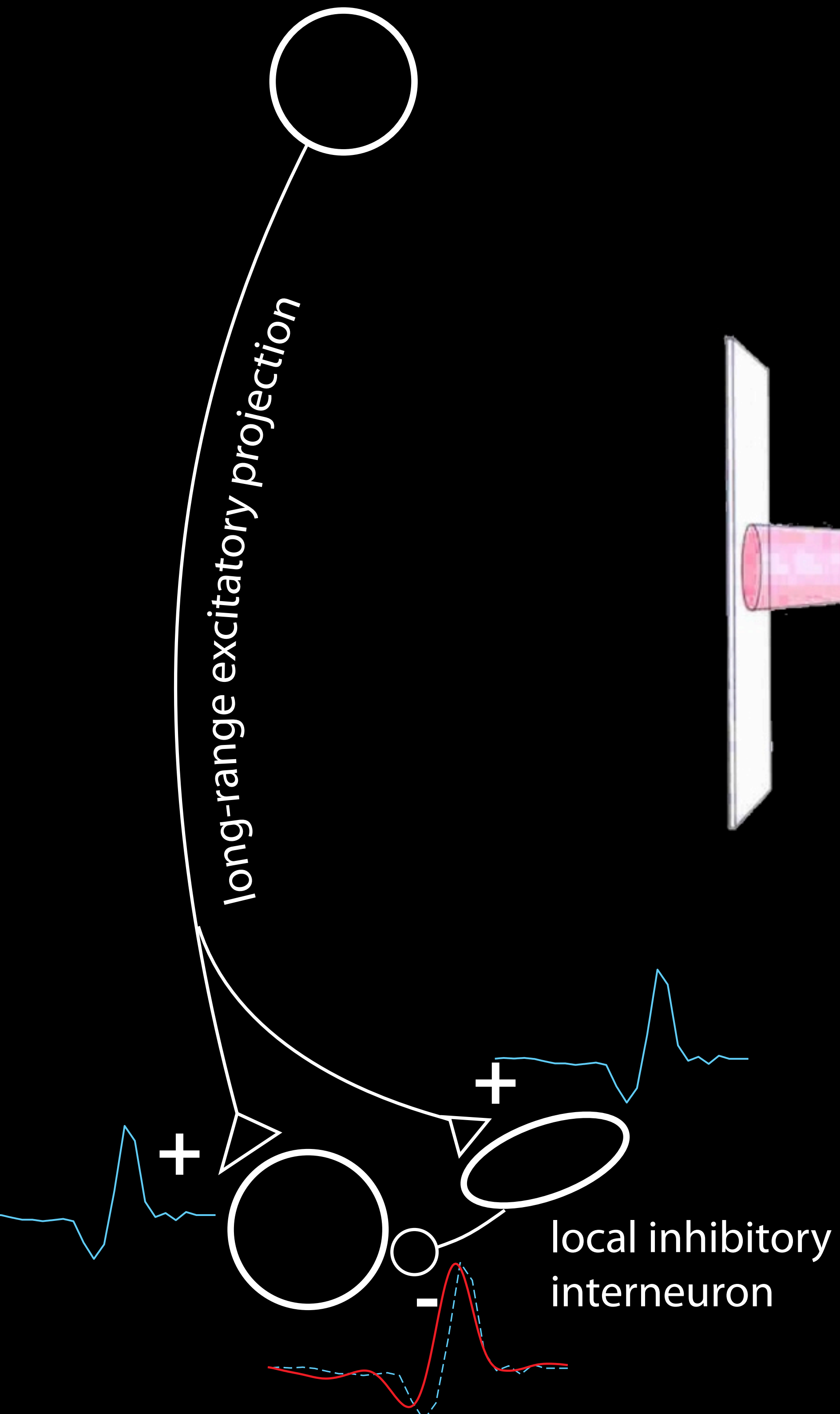
Precision computation

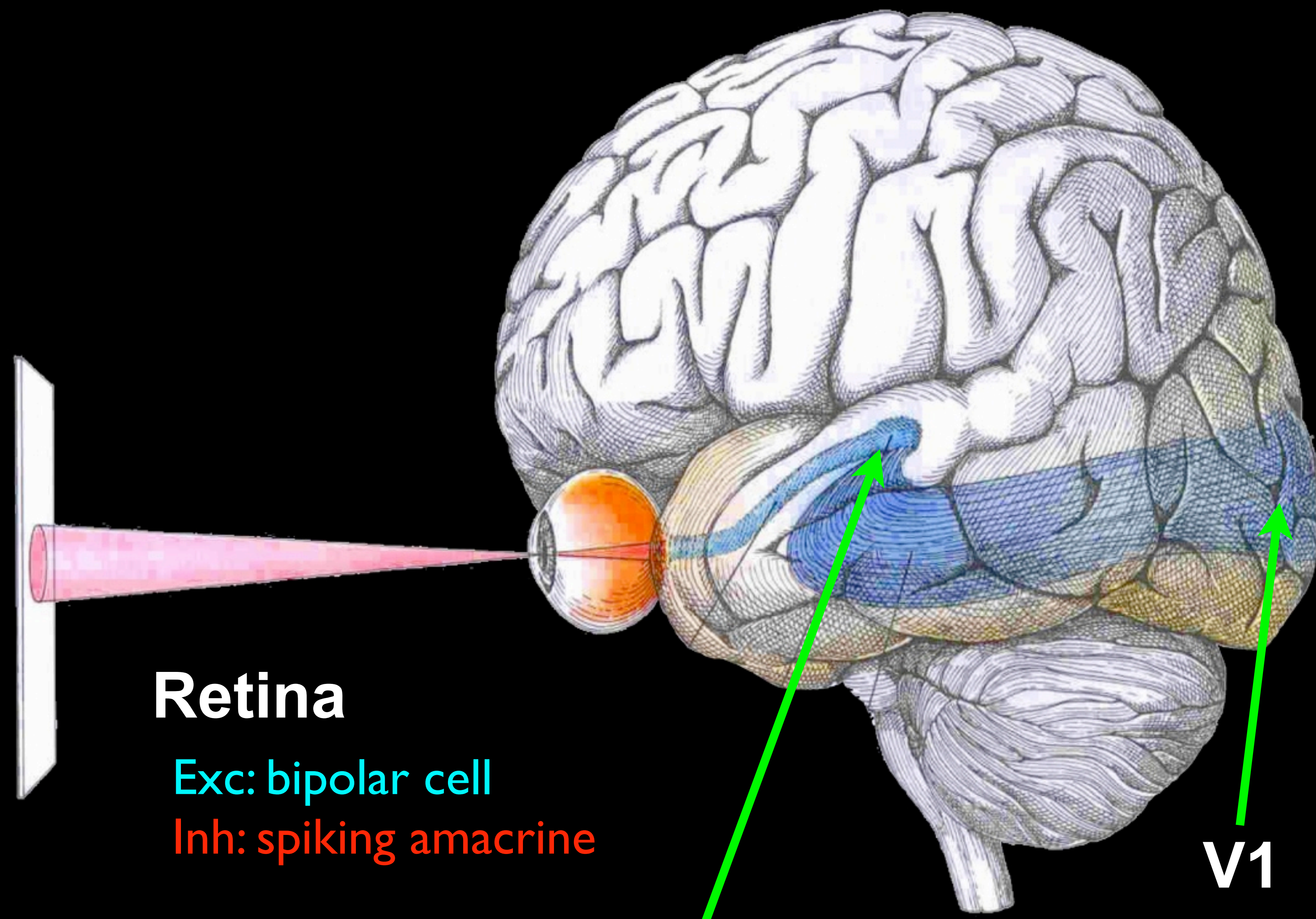




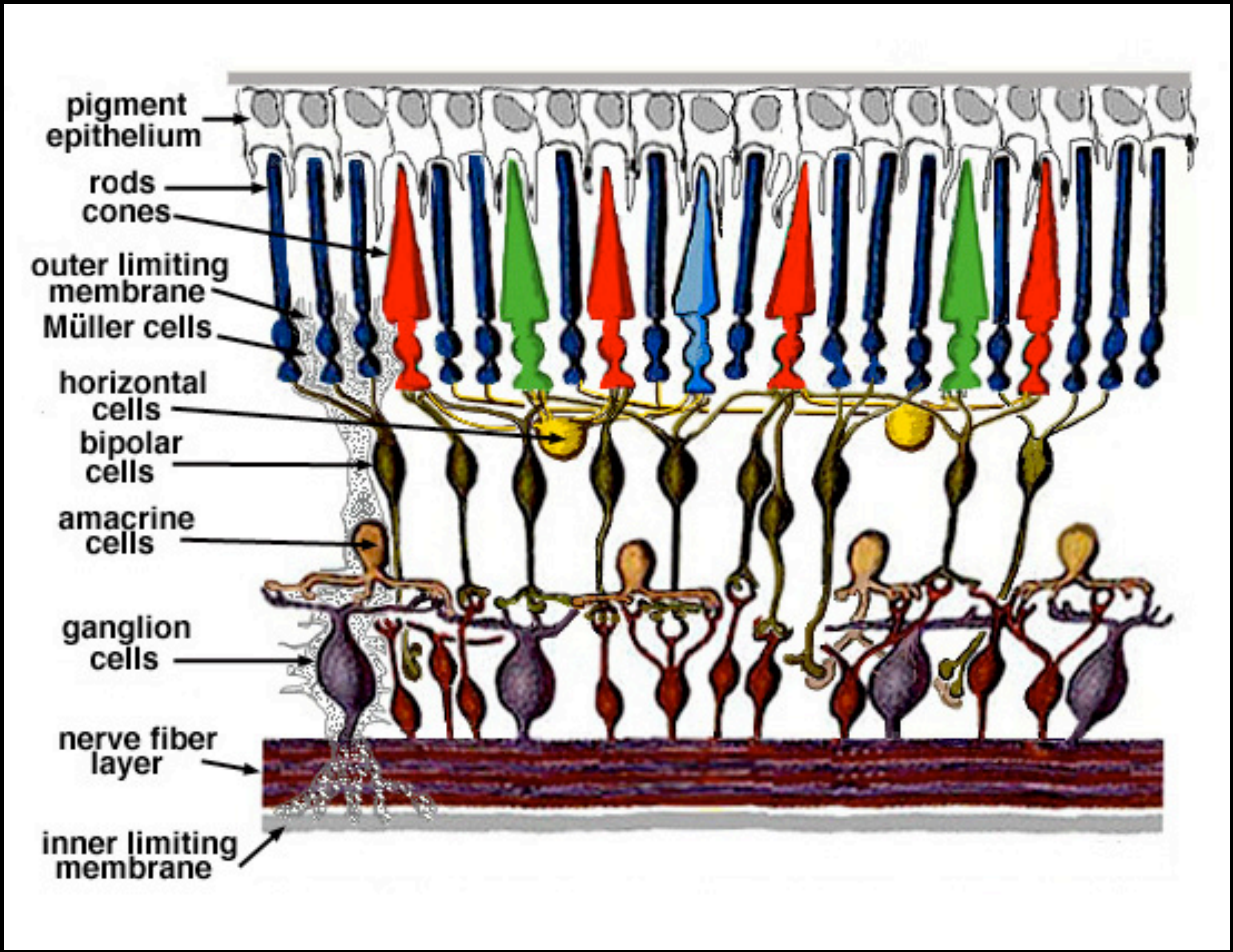


General role of local inhibition?





Circuitry of the retina



OUTER PLEXIFORM LAYER

Role in spatial processing?

INNER PLEXIFORM LAYER

Role in temporal processing?

Conclusions/Parting Thoughts

1. Visual neuron modeling
   - Don't forget the LN model -- it is everywhere
   - Basis for sensory models in neuroscience ("minimal model")

2. Neuroscience has been (but no longer is?) stuck with standard statistics
   - Brought field to where it is (VERY USEFUL) but … could not go much further
   - Neuroscience-statisticians are having large impact on basic science (Emory Brown, Liam Paninski, Rob Kass, Valerie Ventura, Han Amarsingham,…)

3. Maximum likelihood modeling
   - System of models that have smooth likelihood surface
   - Ability to solve higher-order models with limited data