Active dendrites stochastic neuronal model

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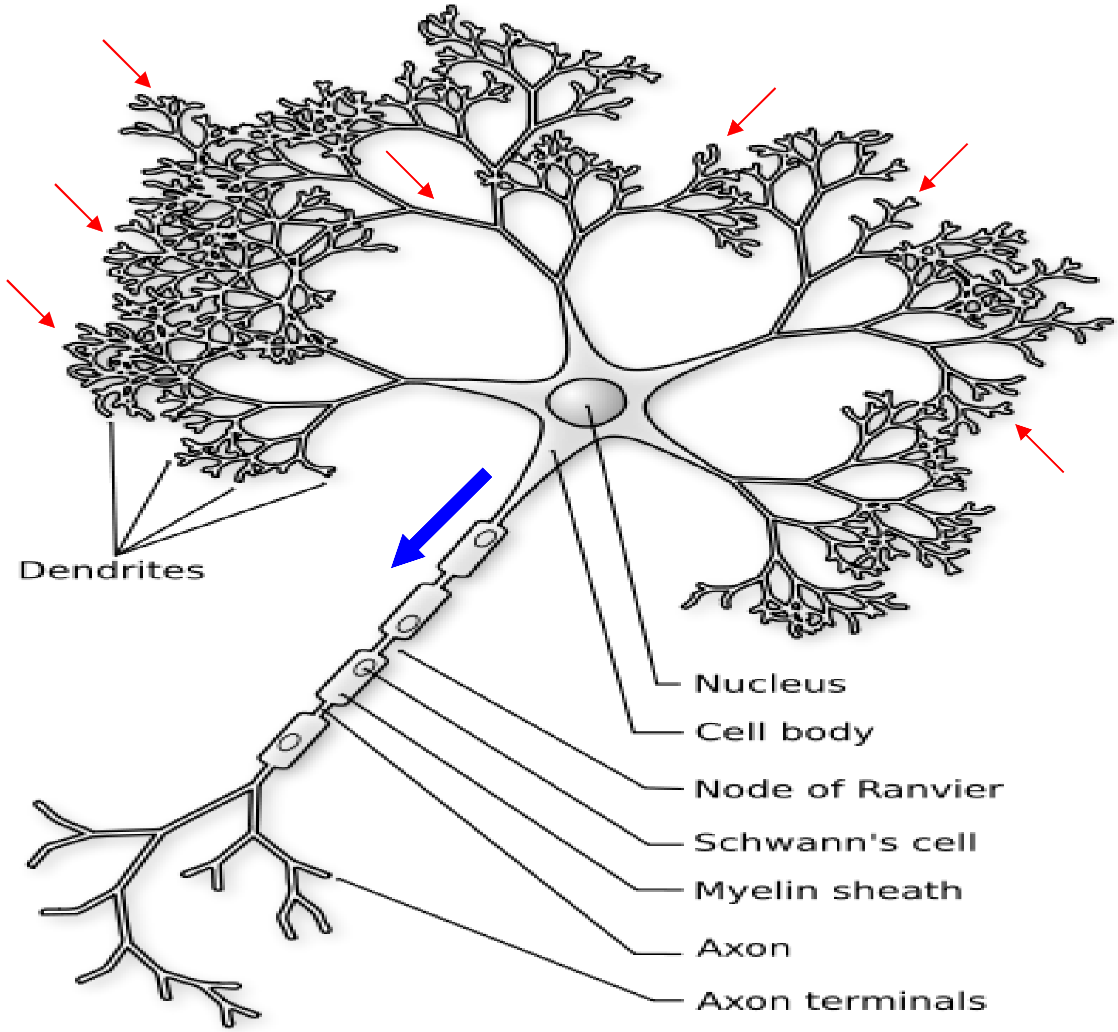
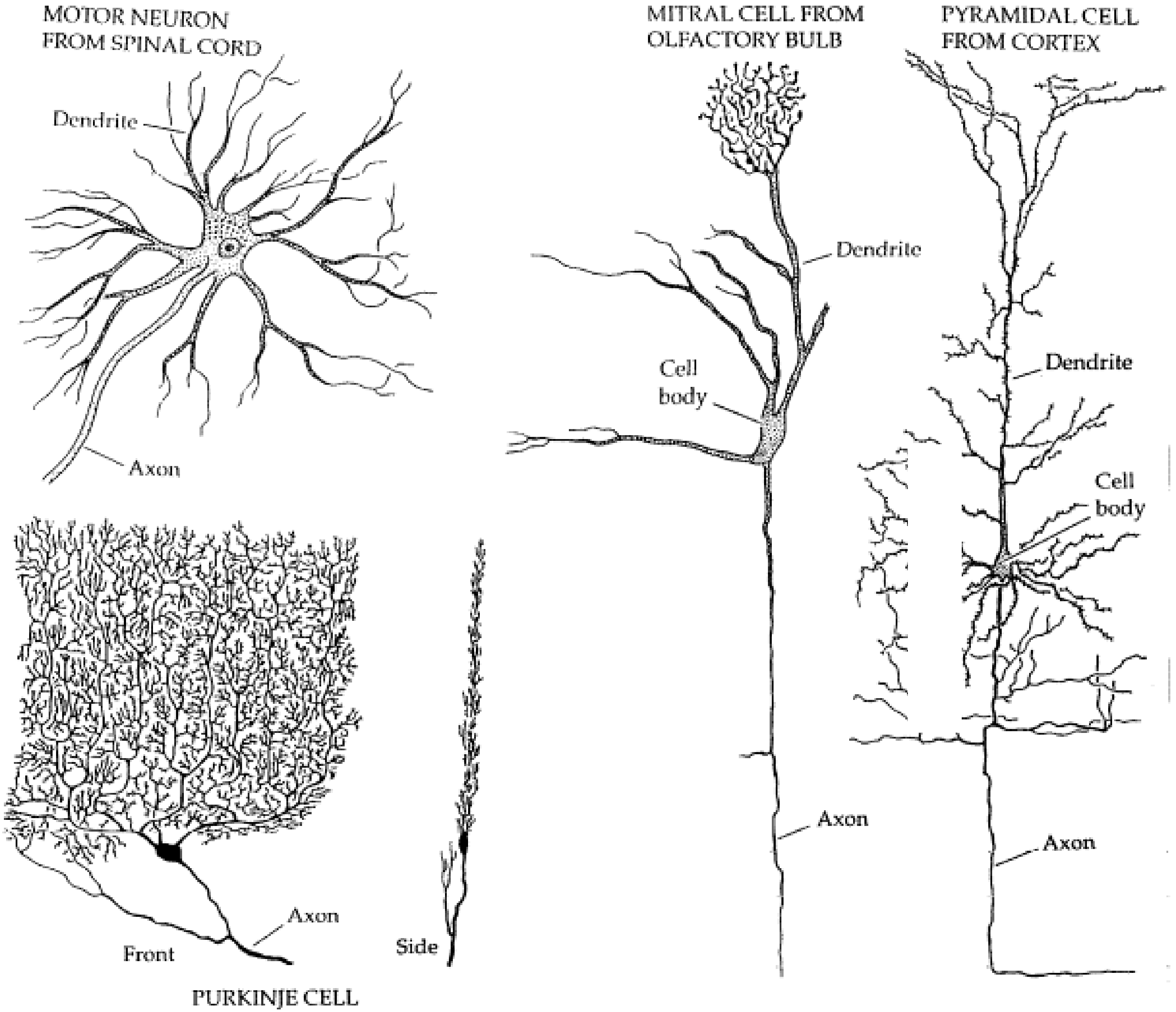
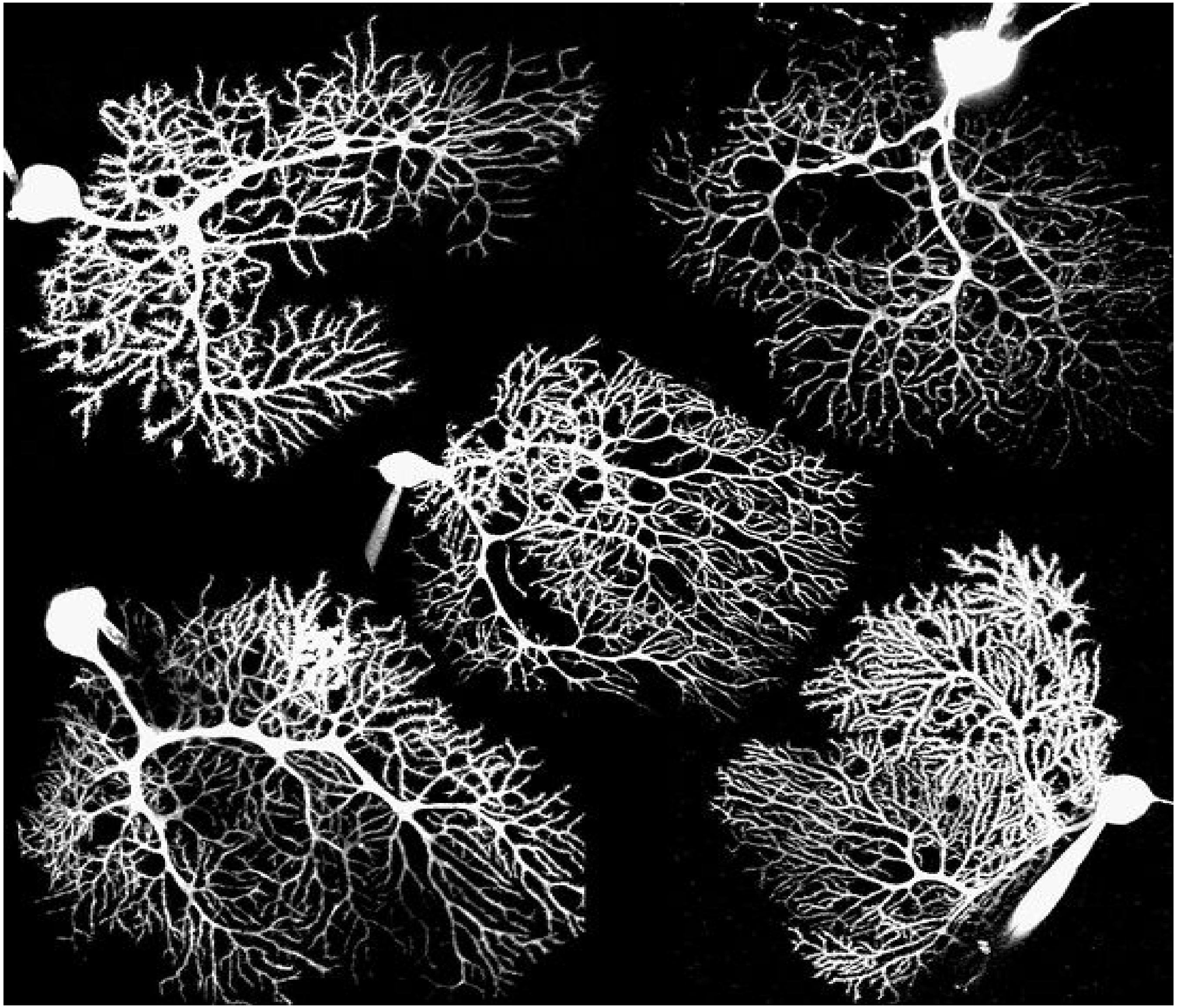

Dendrites
Nucleus
Cell body
Node of Ranvier
Schwann's cell
Myelin sheath
Axon
Axon terminals

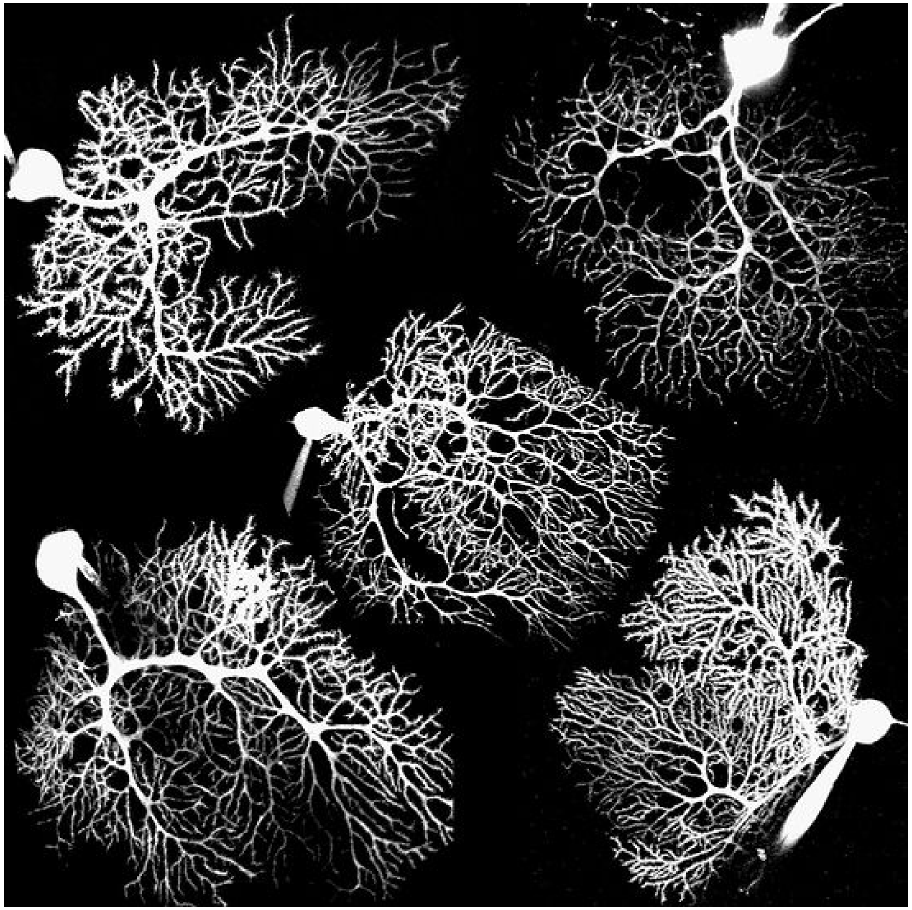
Neurons ~10.000 types



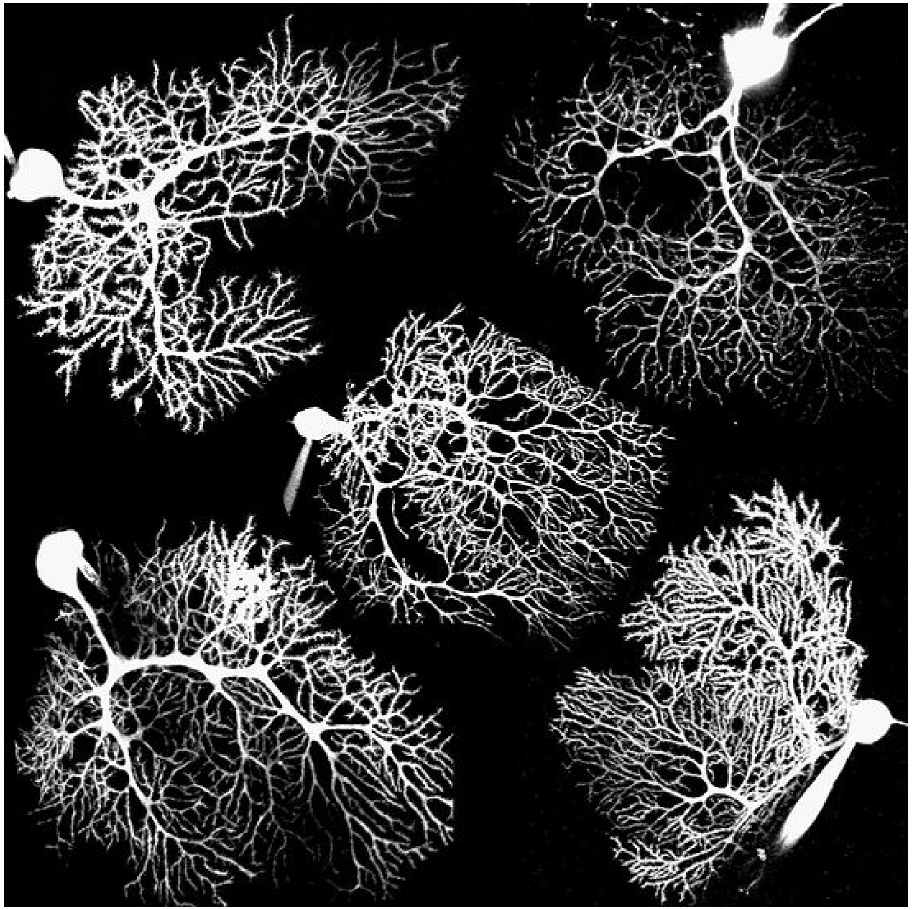
Dendrites: perhaps the most important neuronal feature



- Voltage summation
- Coincidence detectors
- Biological logic gates
- Learn modulation



1. improbable fine tuning of biological parameters
2. not robust over morphology variability



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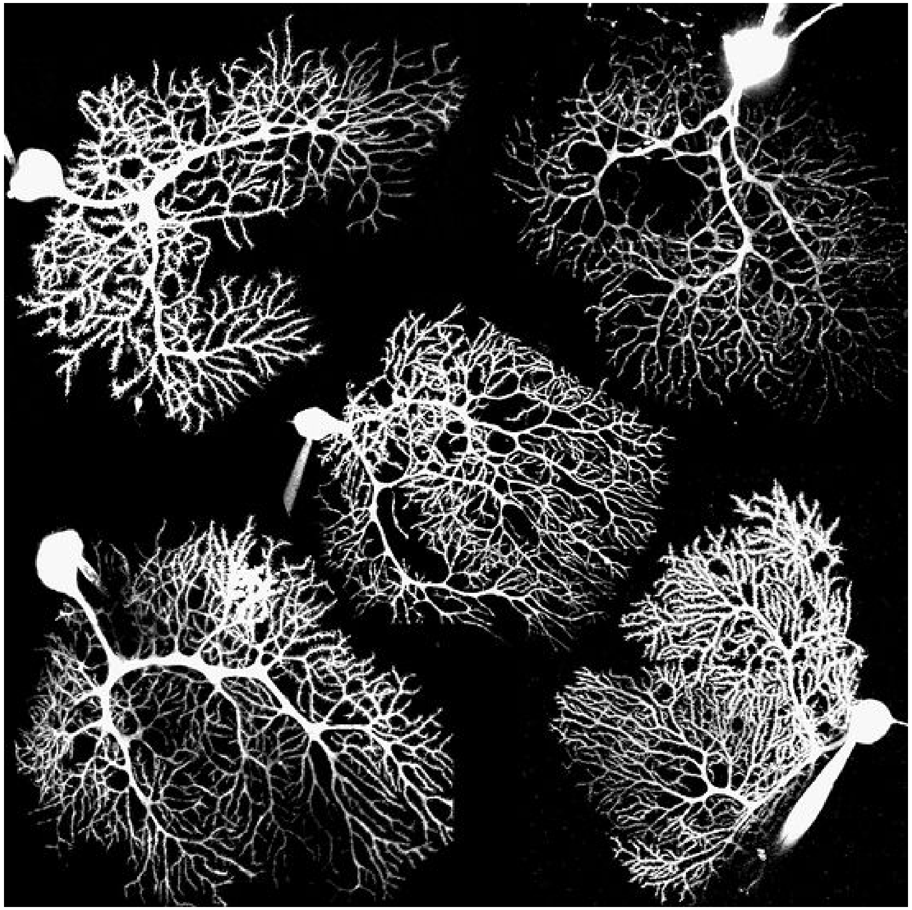

1. improbable fine tuning of biological parameters
2. not robust over morphology variability

Eccles works (1958)

- active conductances
- dendritic spike

Ultimate wish: theory for active dendrites

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- active conductances
- dendritic spike

Ultimate wish: theory for active dendrites

- Sensory stimulus intensity problem
- Stochastic model
- Mathematical formulation

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$$\Delta = 10 \log_{10} \left(\frac{r_{0.9}}{r_{0.1}} \right)$$

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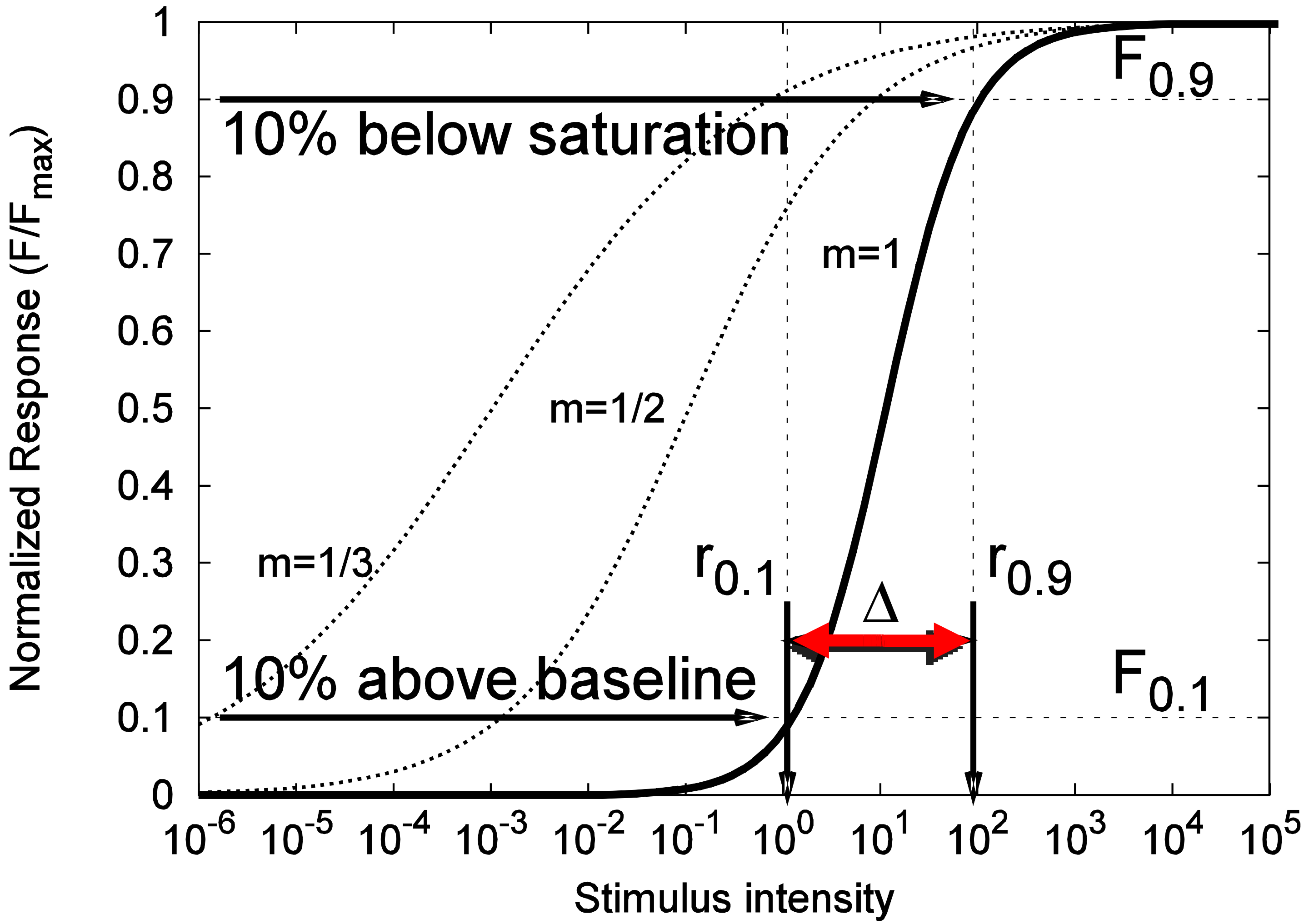
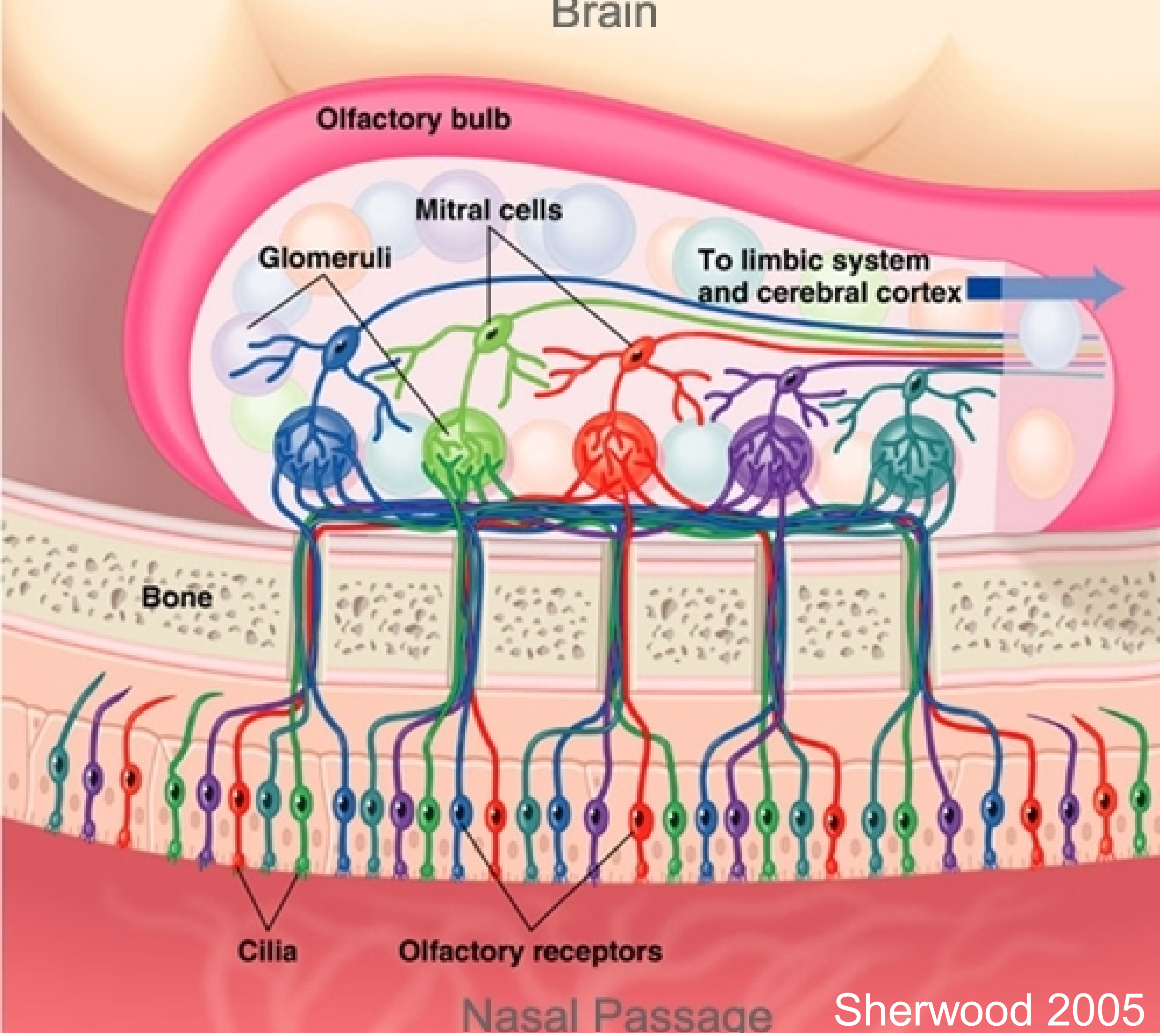
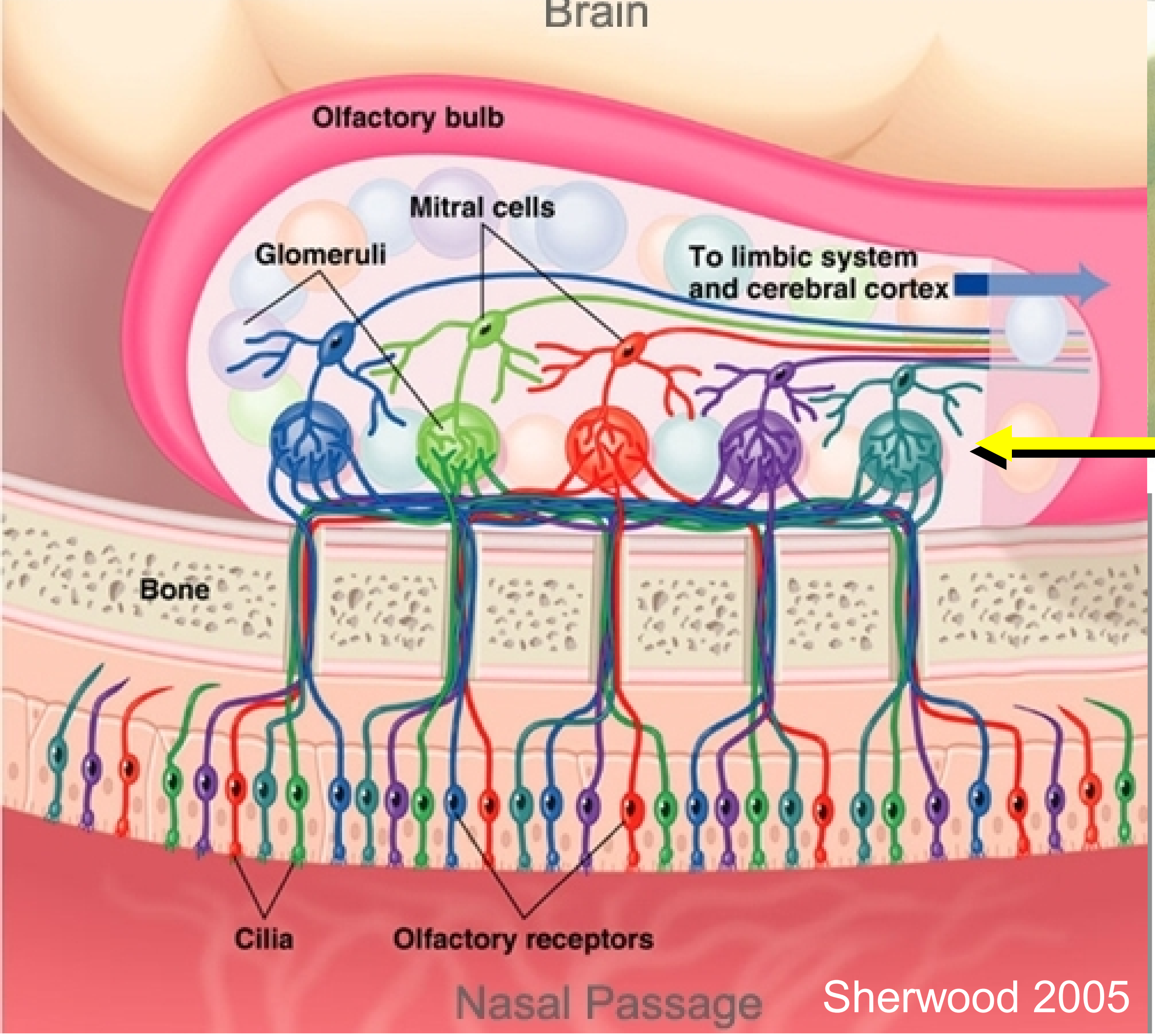
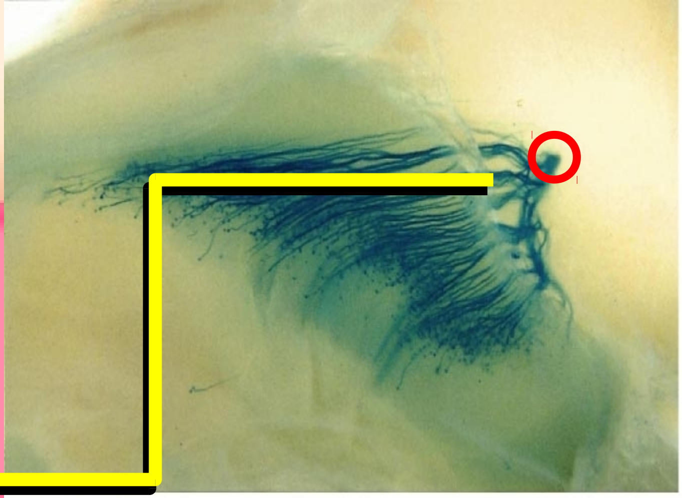
$$F_x = x(F_{max} - F_0) + F_0$$

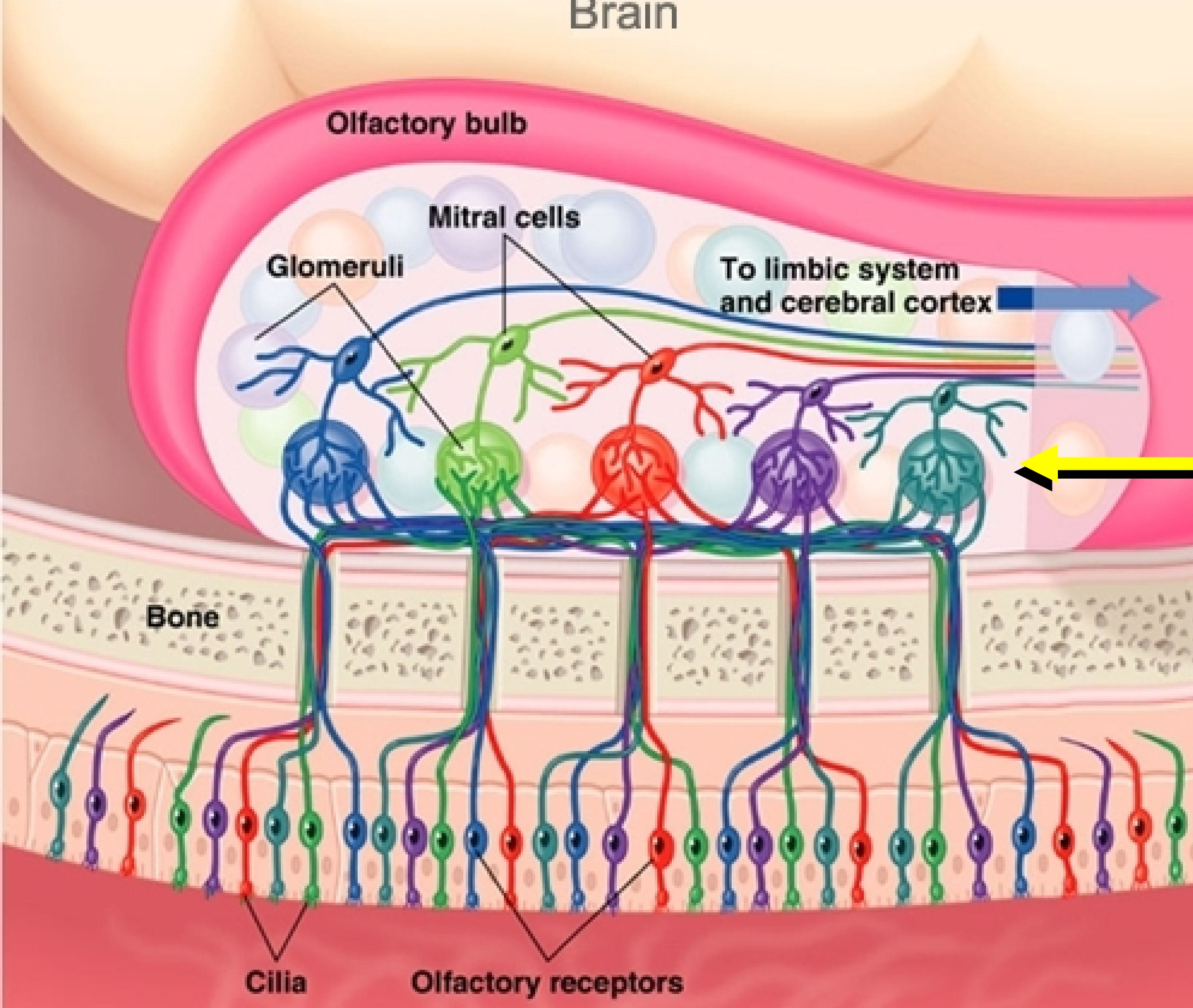


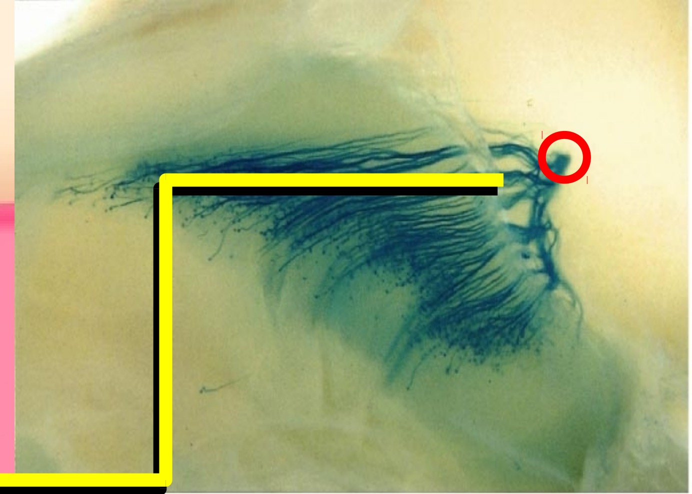

Brain
Olfactory bulb
Mitral cells
Glomeruli
To limbic system
and cerebral cortex
Bone
Cilia
Olfactory receptors
Nasal Passage
Sherwood 2005





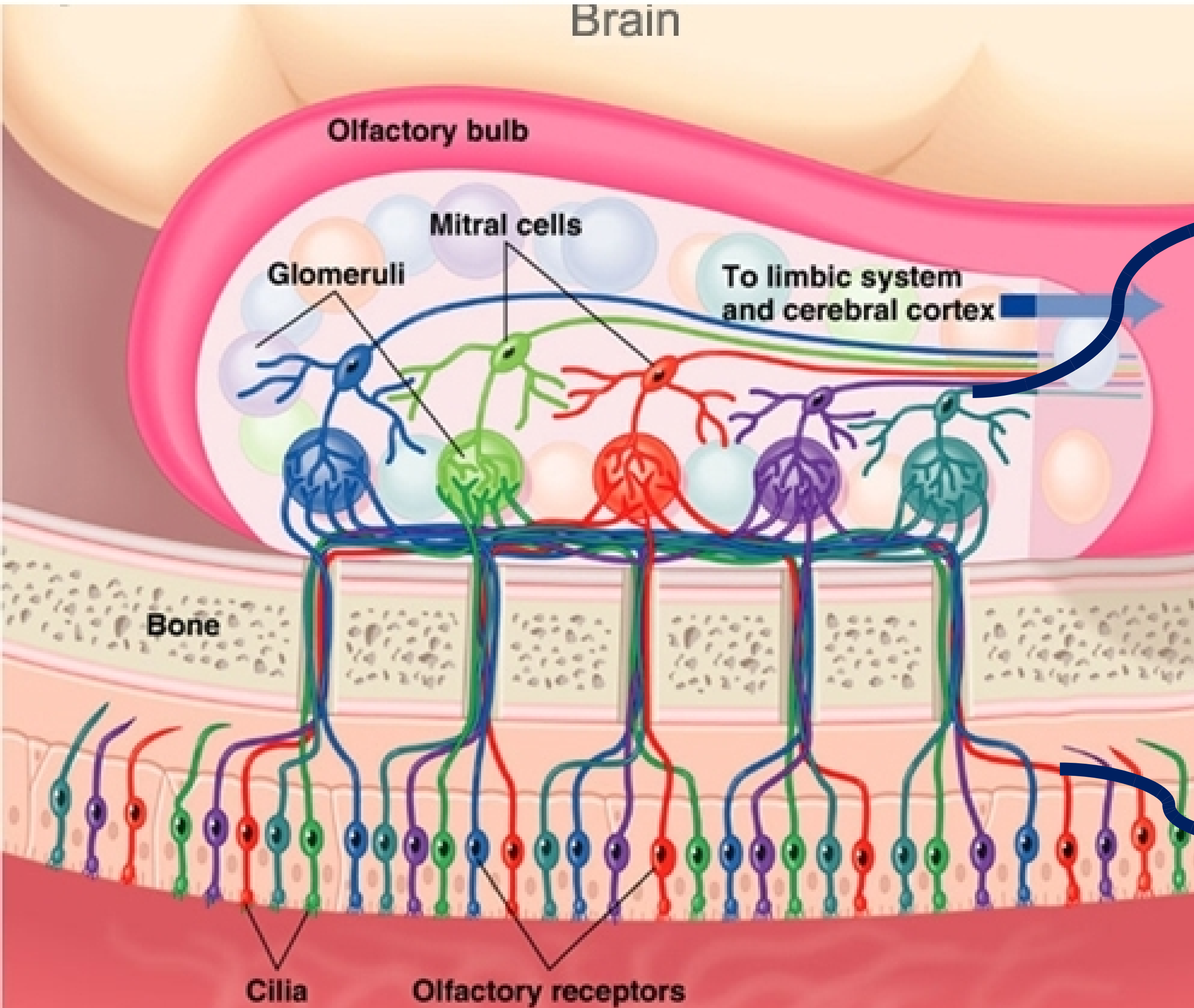
Squire et al. 2003



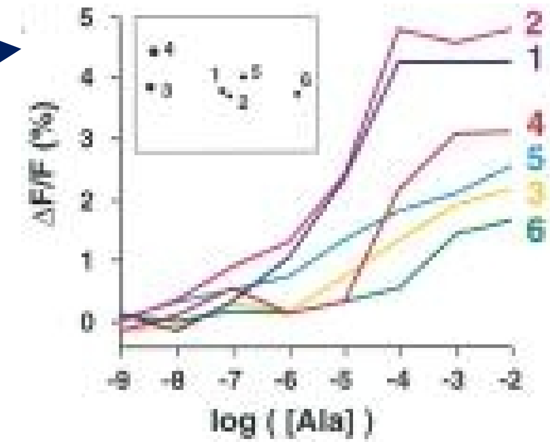


Squire et al. 2003

Kosaka et al. 2001

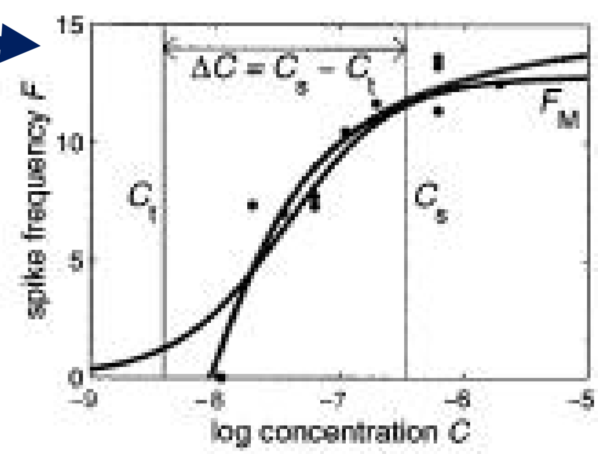


30-50 dB



Friedrich et al 1997

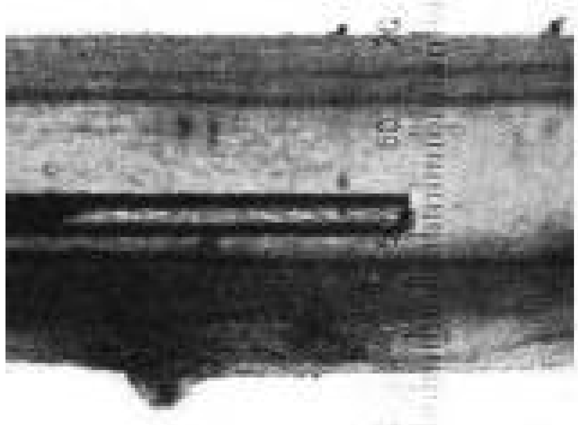
10-20 dB

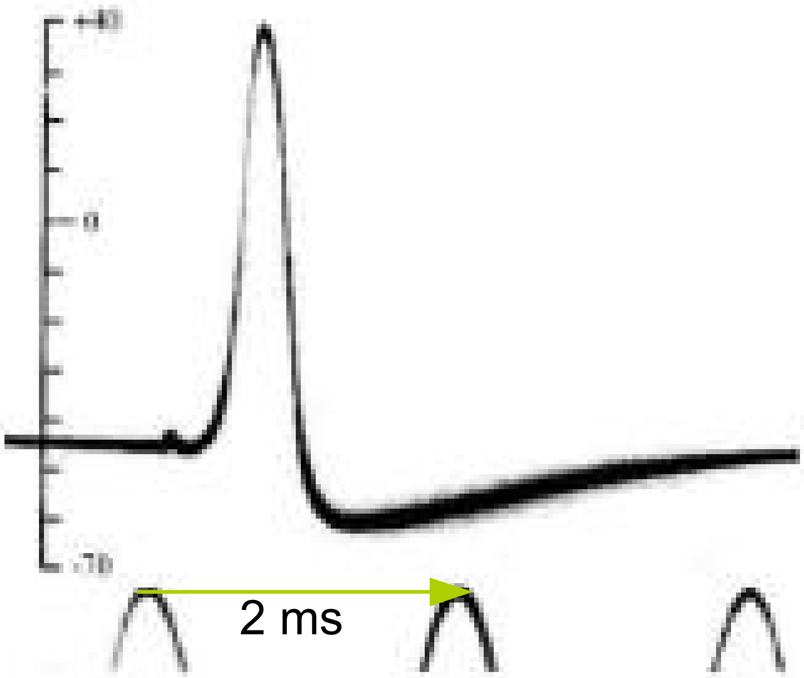


J.P.Rospars et al. 2000

- Sensory stimulus intensity problem
- Stochastic model
- Mathematical formulation

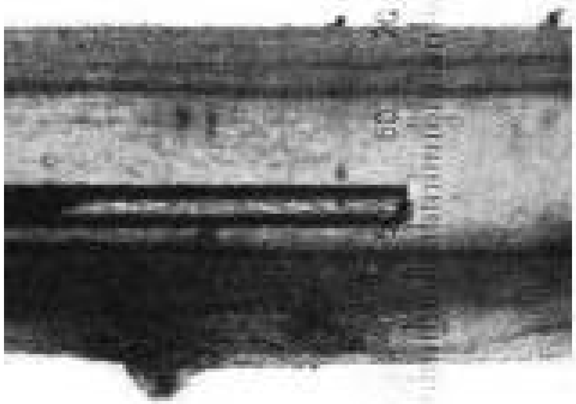
Hodgkin – Huxley (1939)

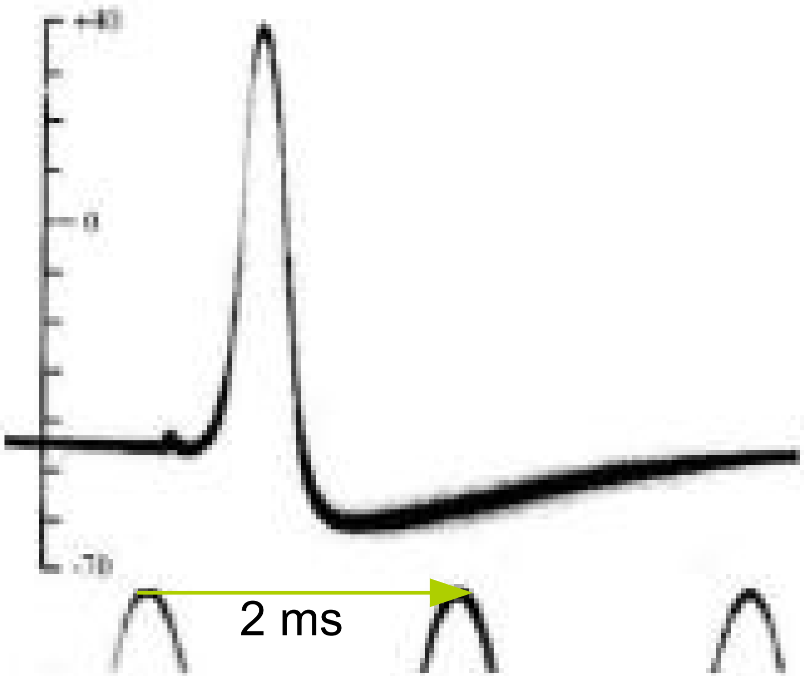




- Active membranes
  - coupled non-linear differential equations
  - electric potential and ionic conductances

Hodgkin – Huxley (1939)

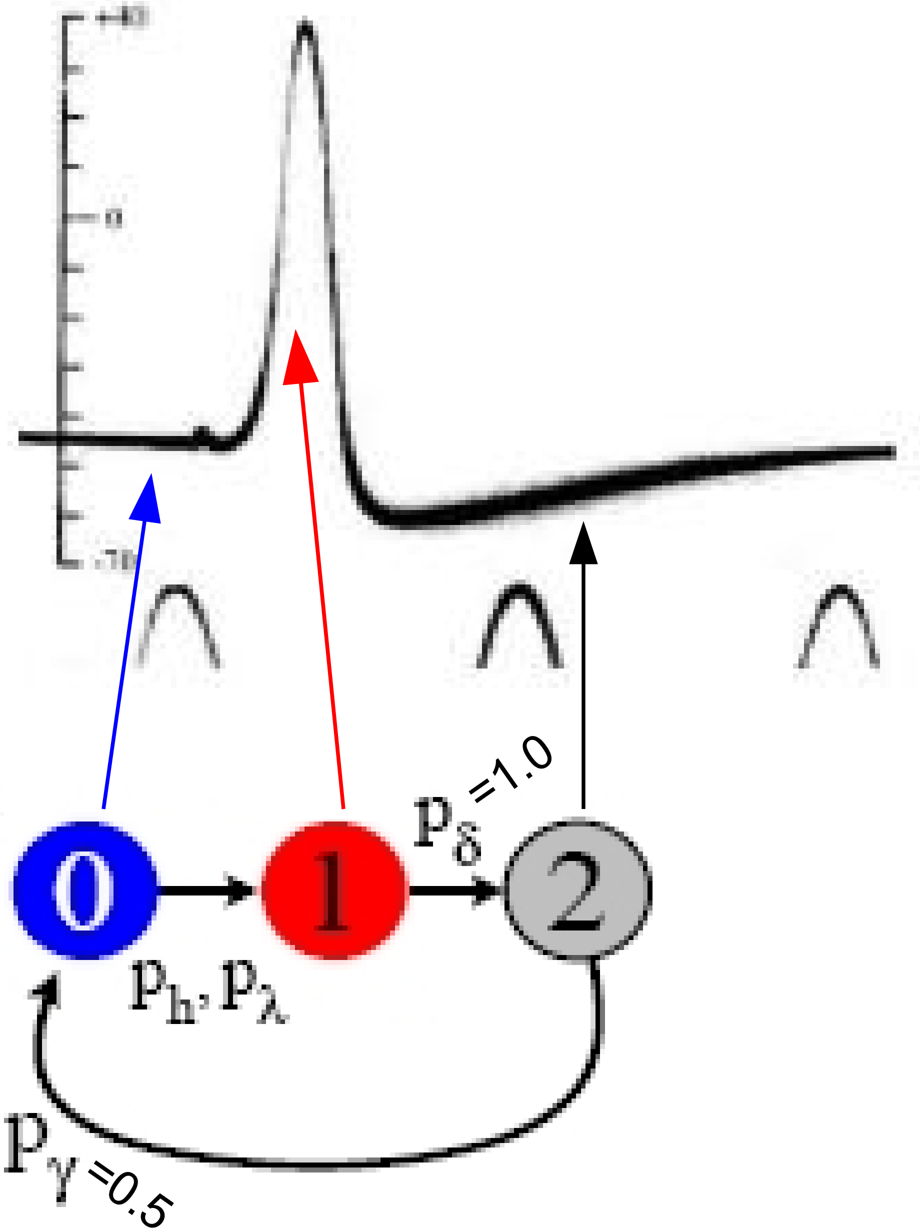




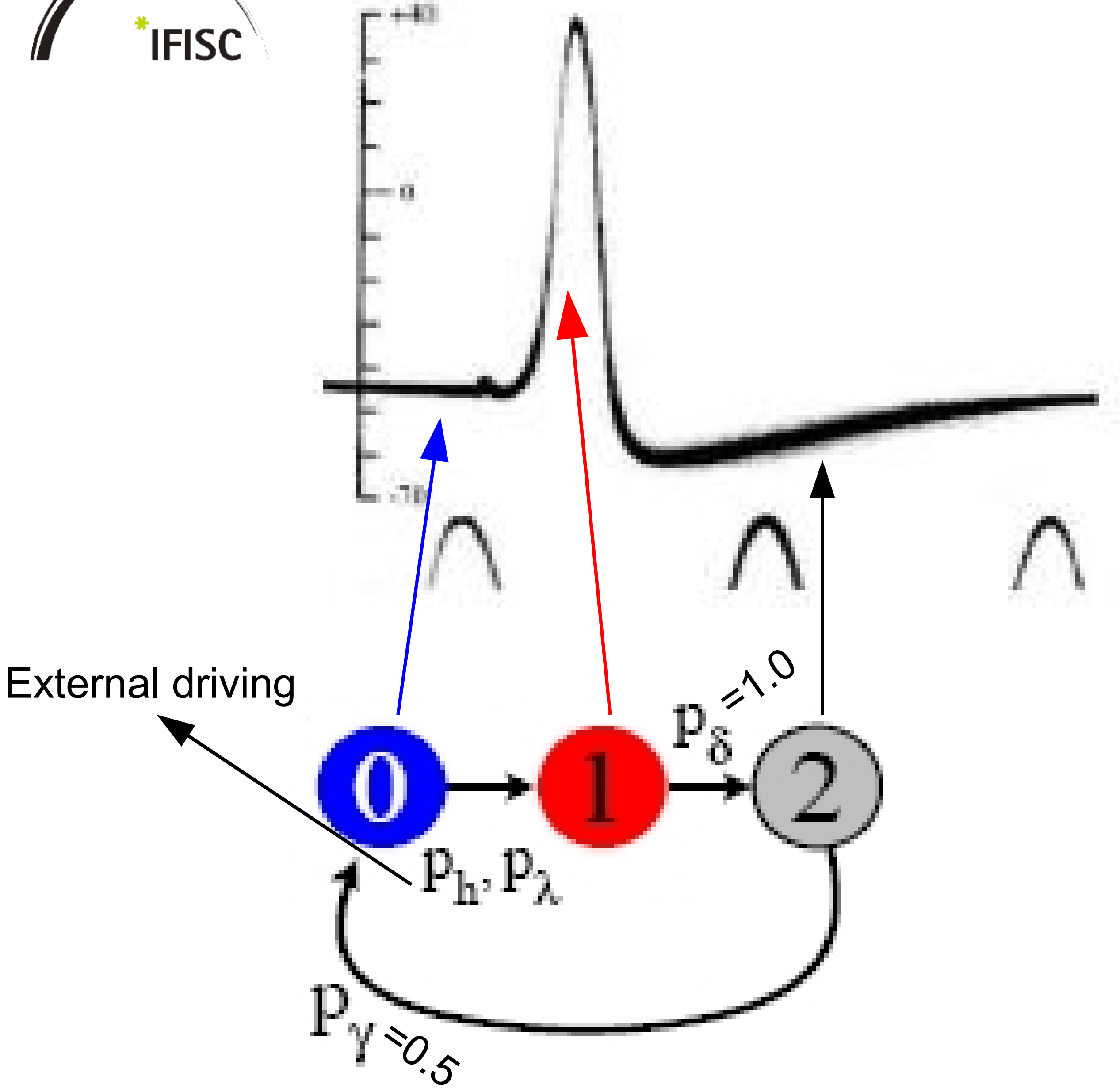
- Active membranes
  - coupled non-linear differential equations
  - electric potential and ionic conductances

- Detailed compartmental modelling

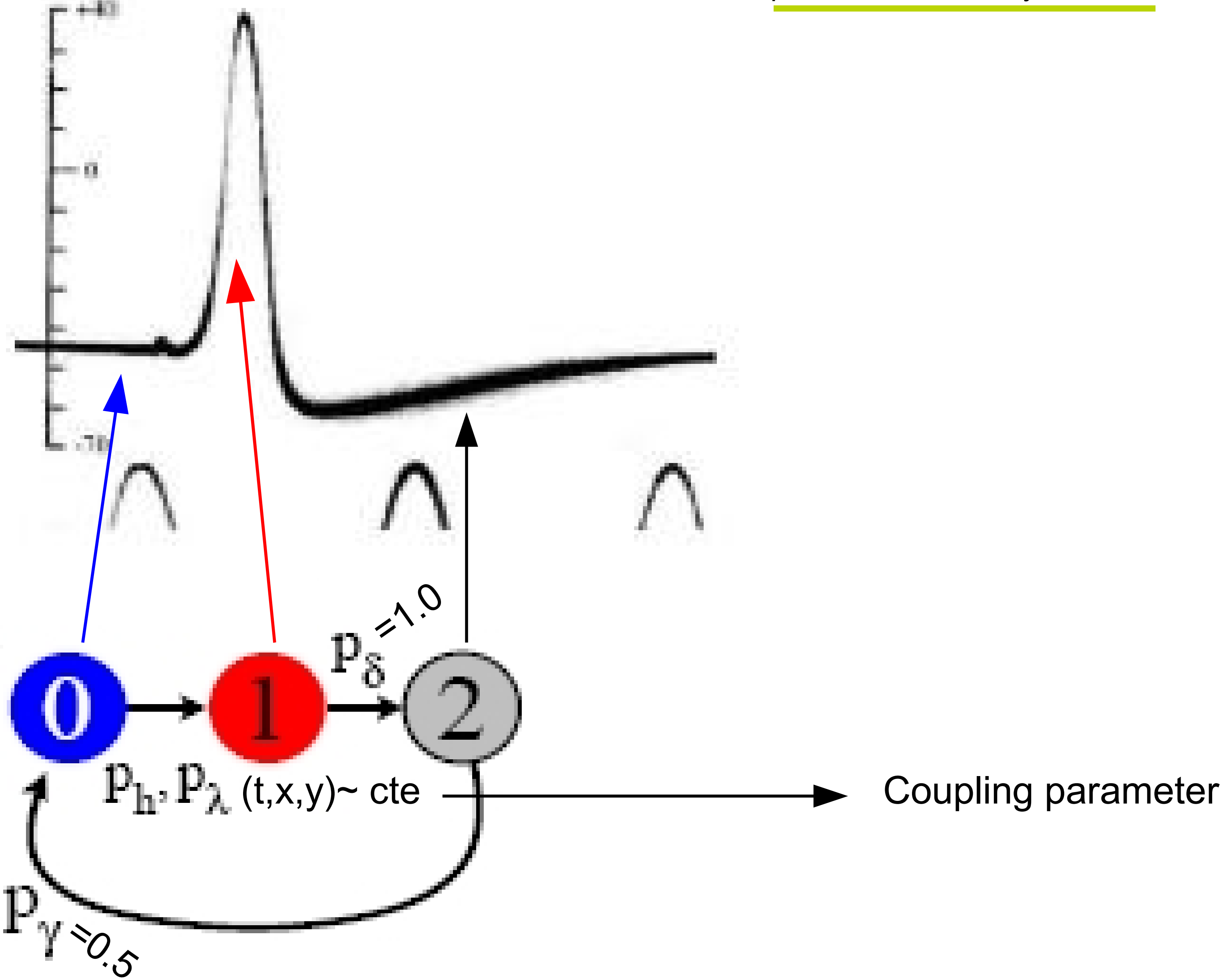
- Spatially extended excitable system
- Simple non-linear dynamics
- Collective behavior

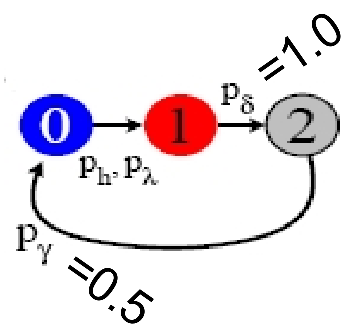


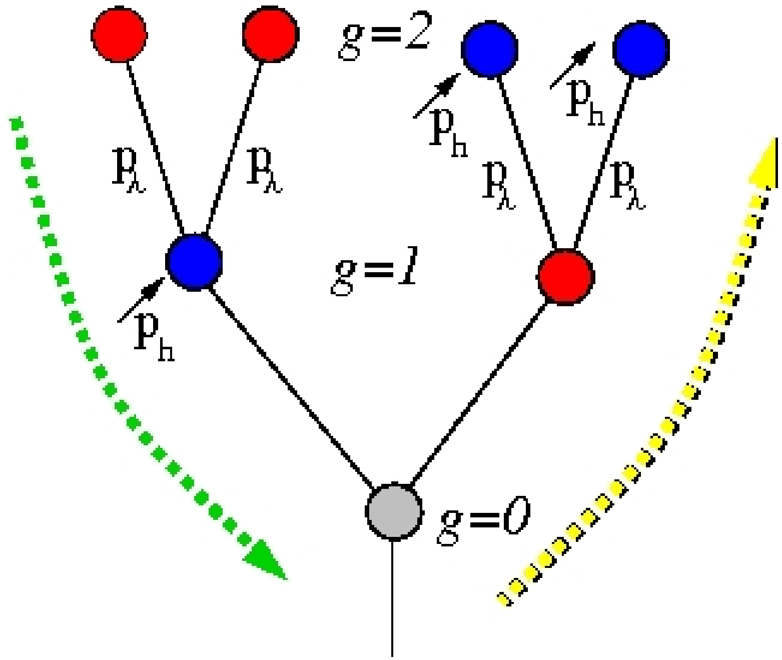
0
1
2
pδ =1.0
ph, pλ
pγ =0.5


External driving
0
1
2
pδ =1.0
ph, pλ
pγ =0.5

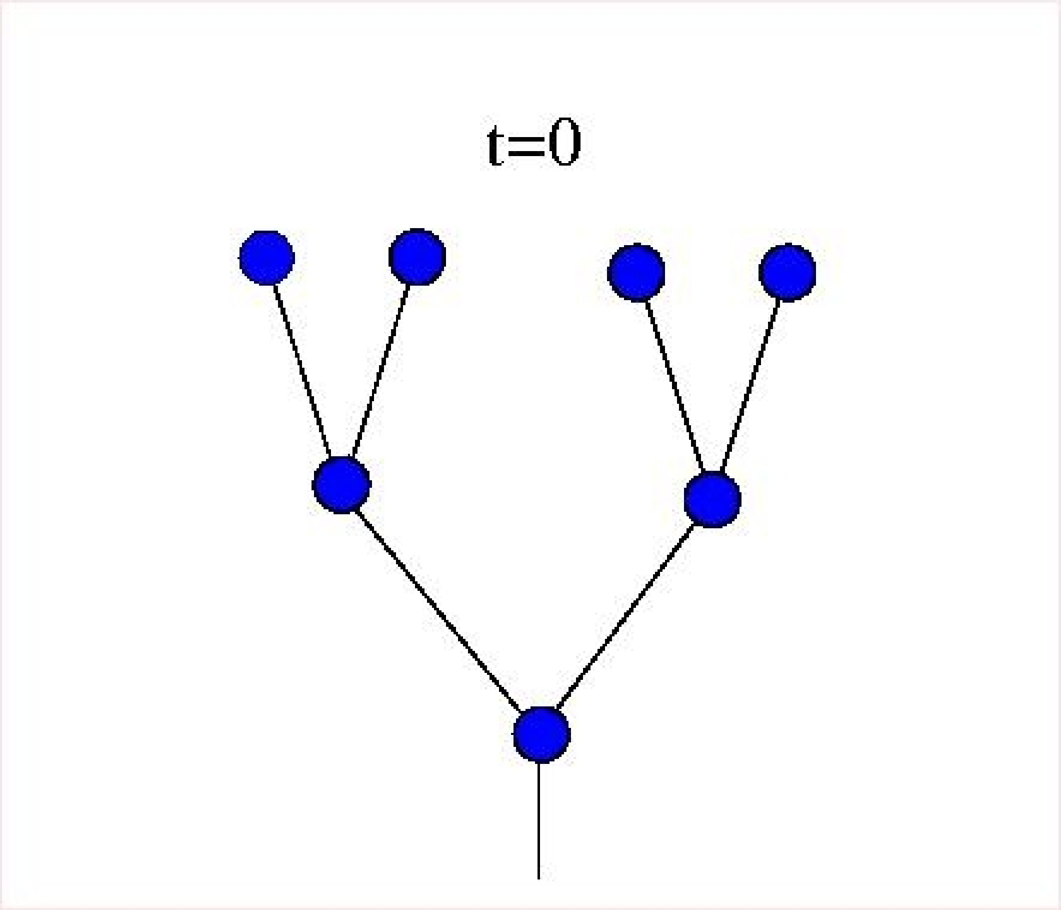
Stochastic process: channel dynamics

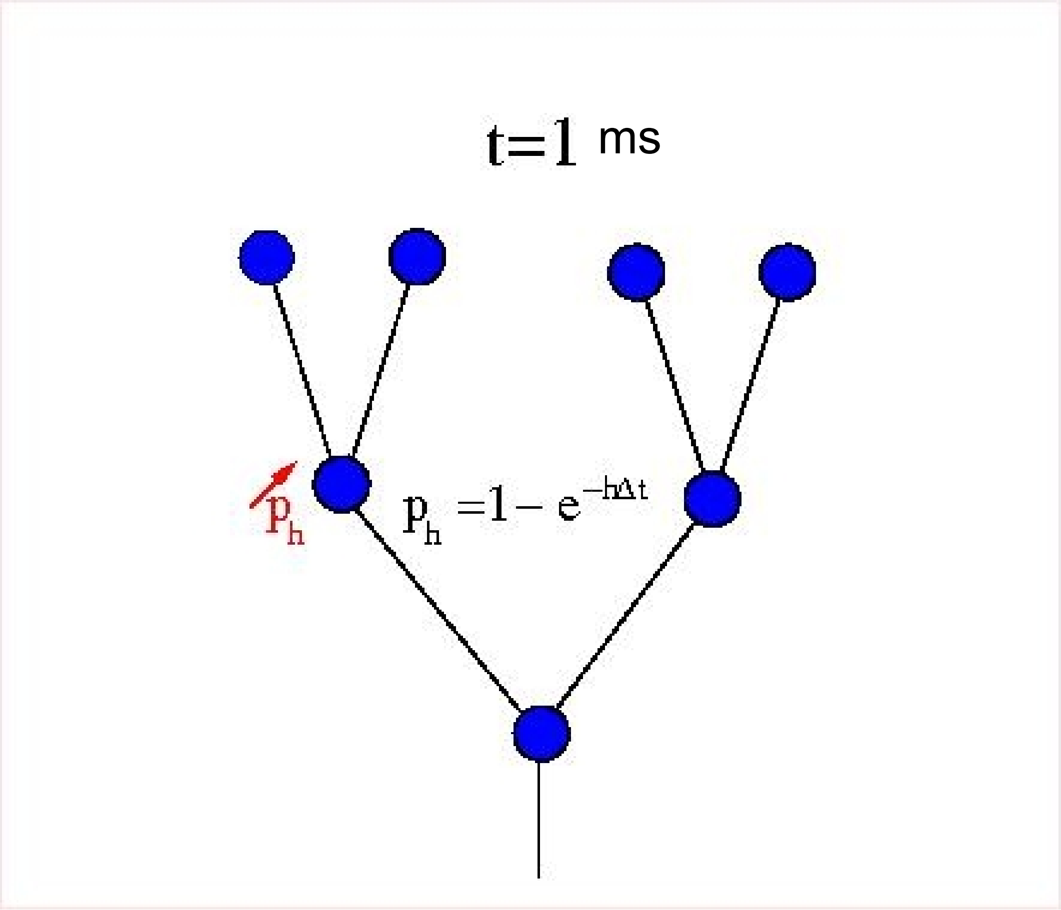


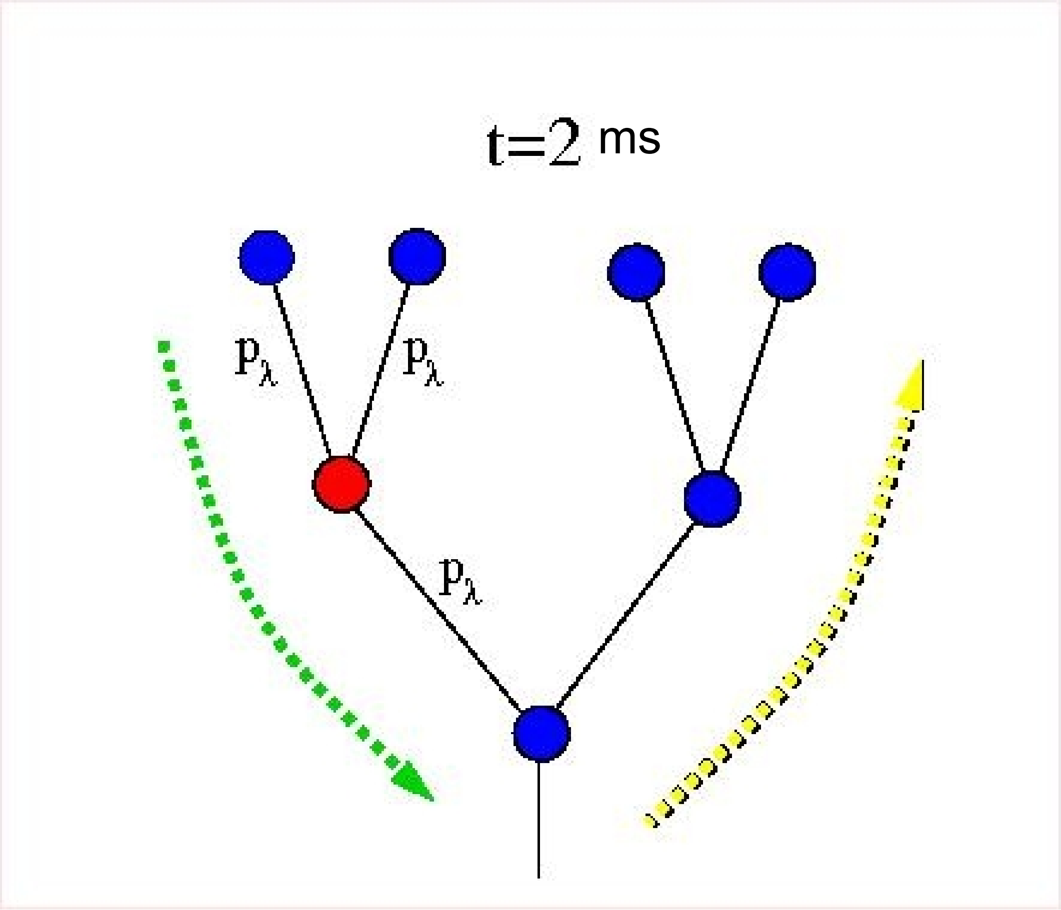

0
1
2
pδ
=1.0
ph, pλ
pγ
=0.5

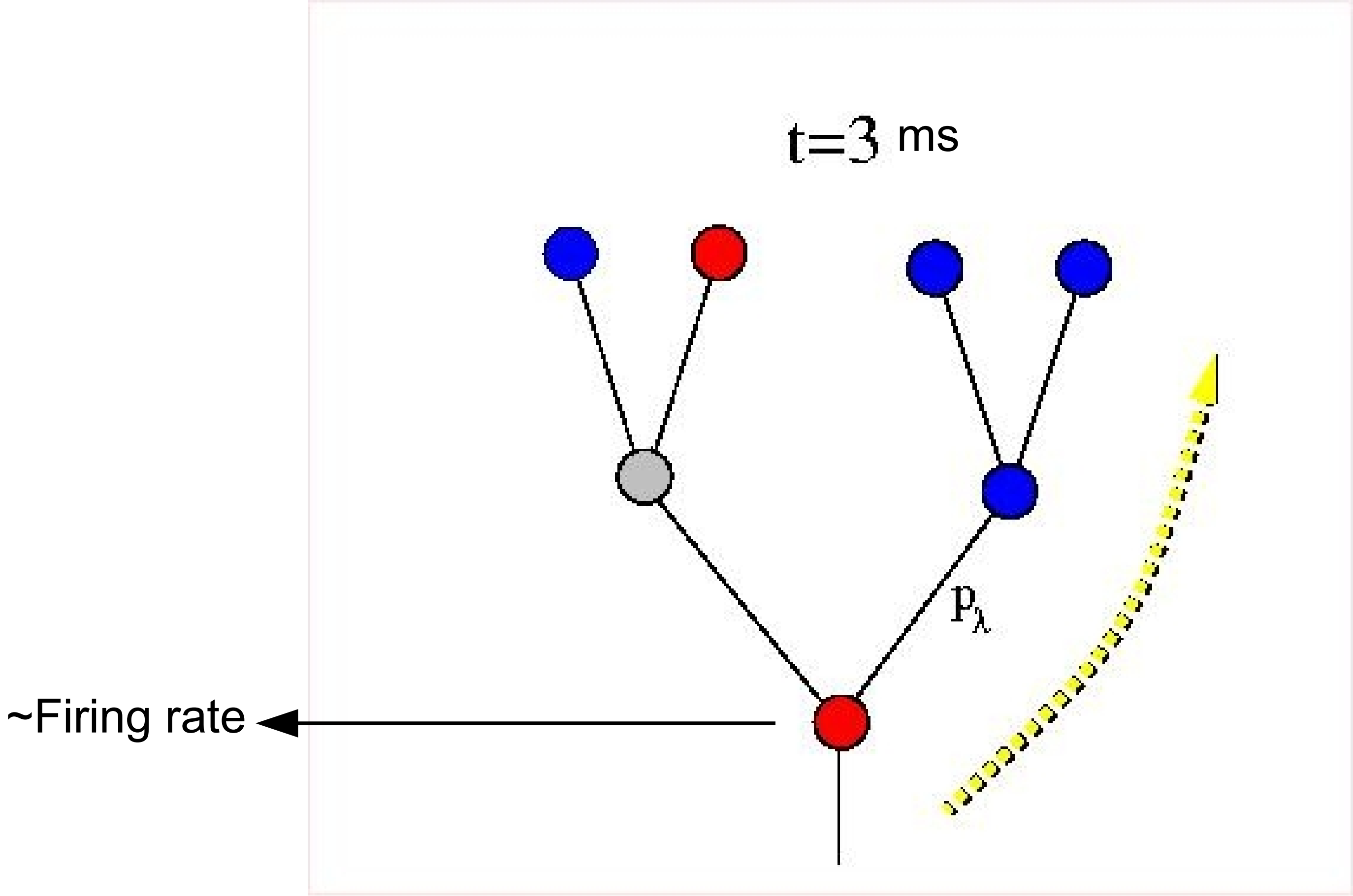

g=2
g=1
g=0
pλ
pλ
pλ
pλ
ph
ph
ph

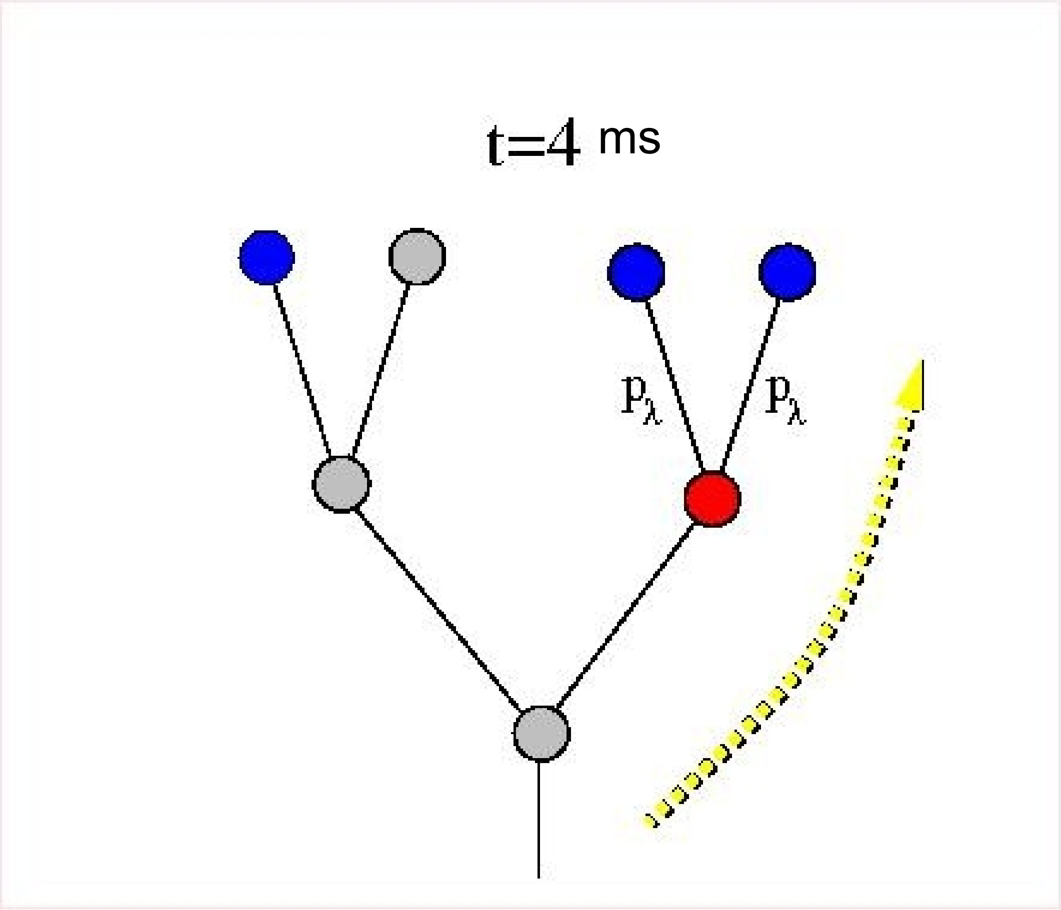
Example:

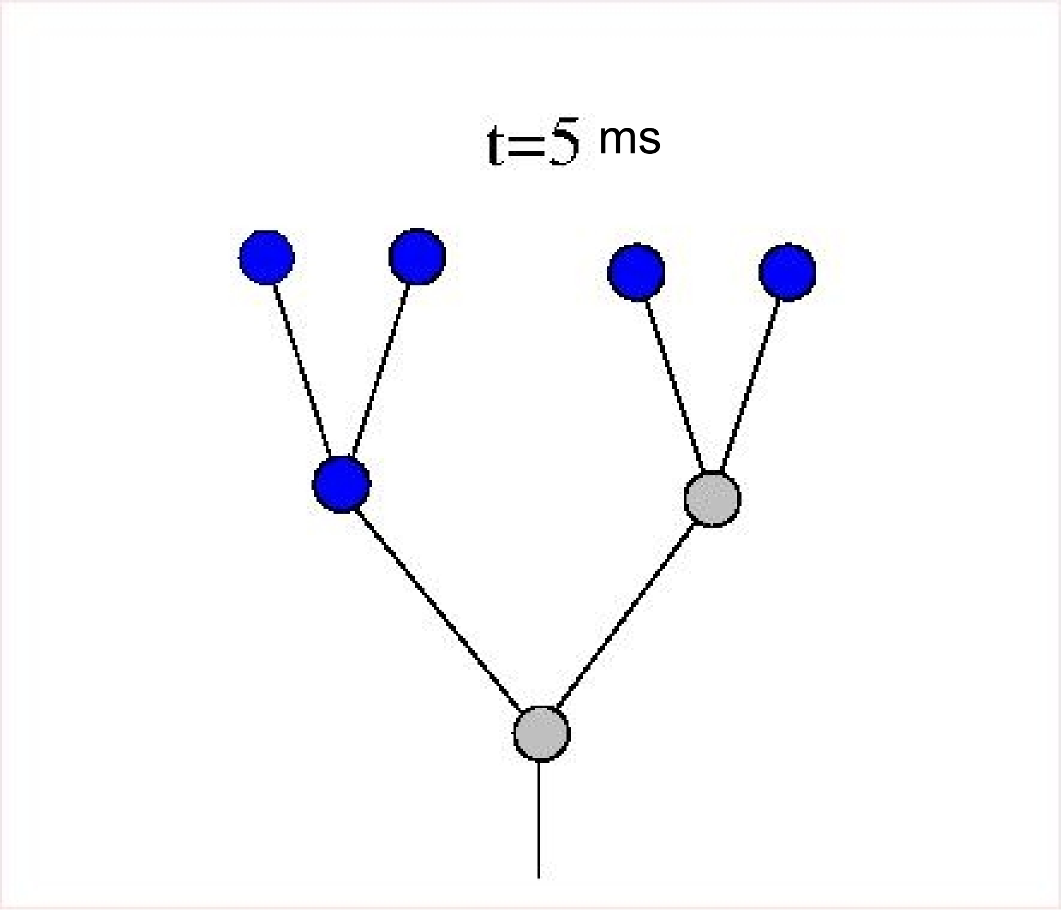


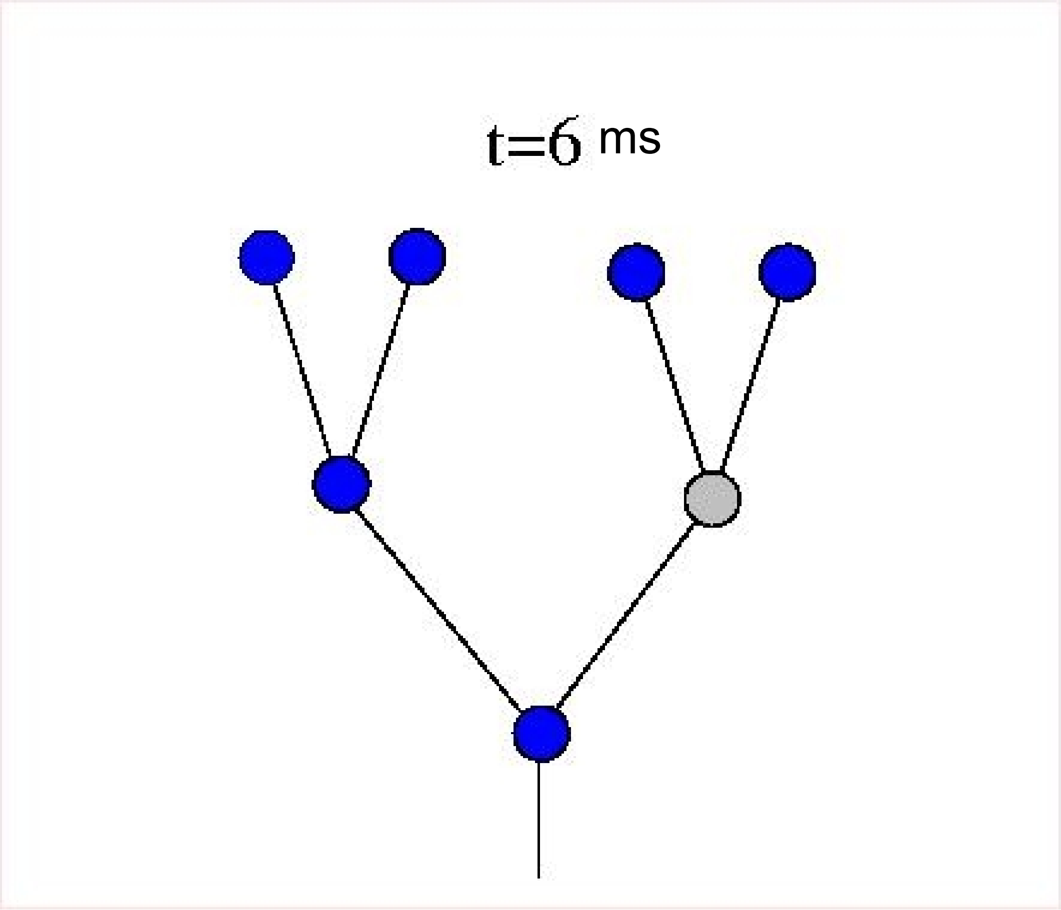

t=1 ms
p_h
$p_h = 1 - e^{-h\Delta t}$

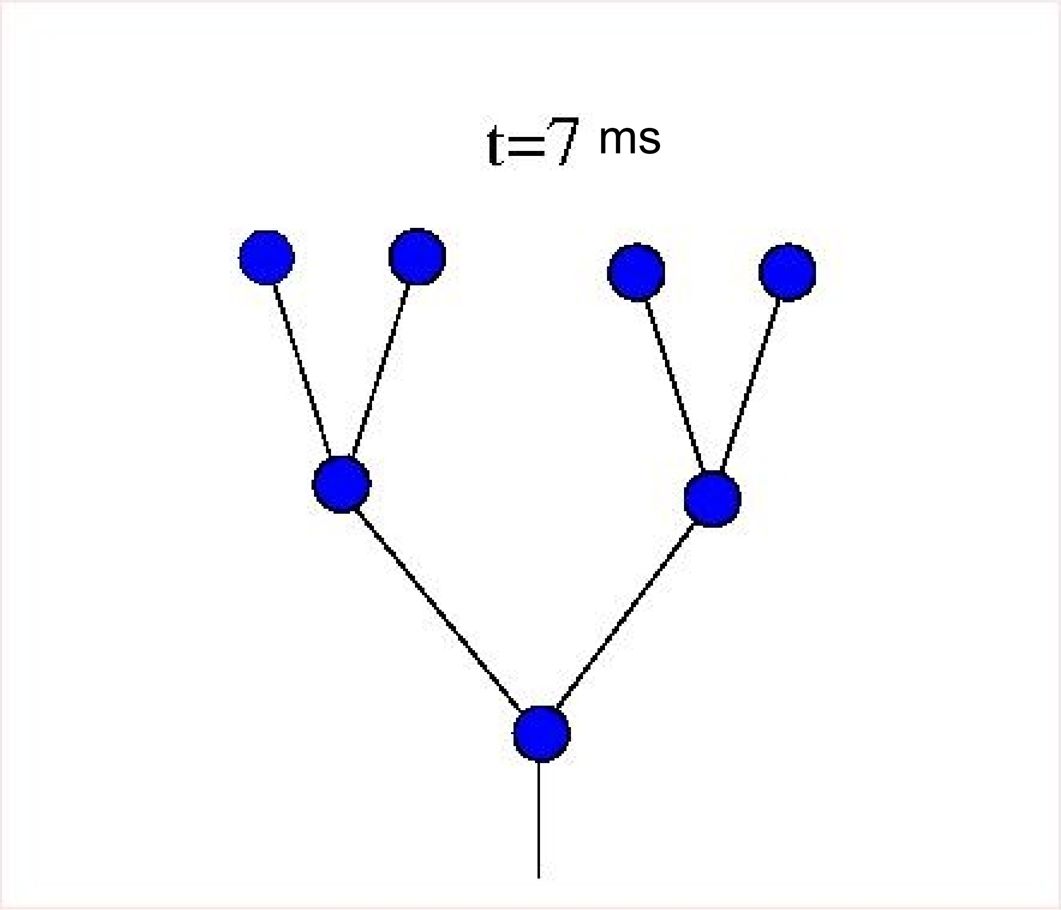

t=2 ms
p_λ
p_λ
p_λ

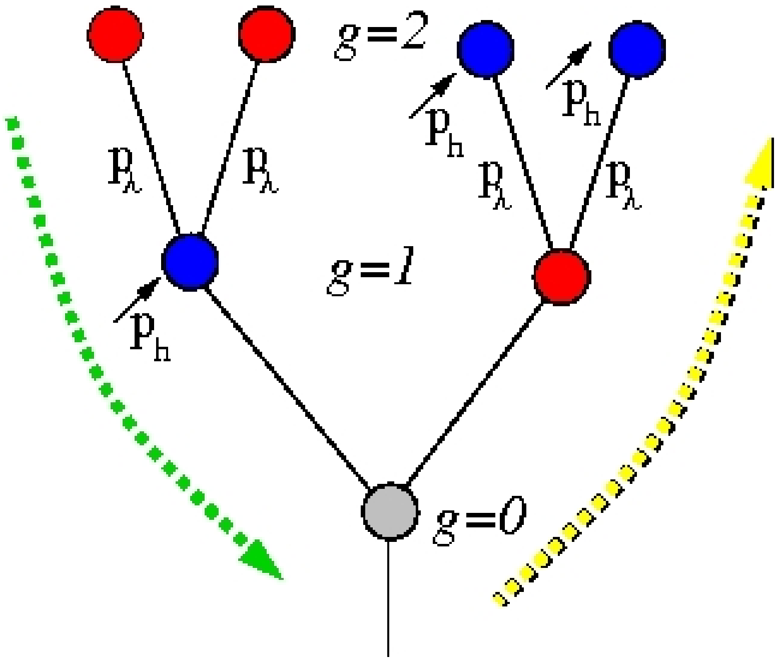

t=3 ms
p_λ
~Firing rate


t=4 ms
p_λ
p_λ

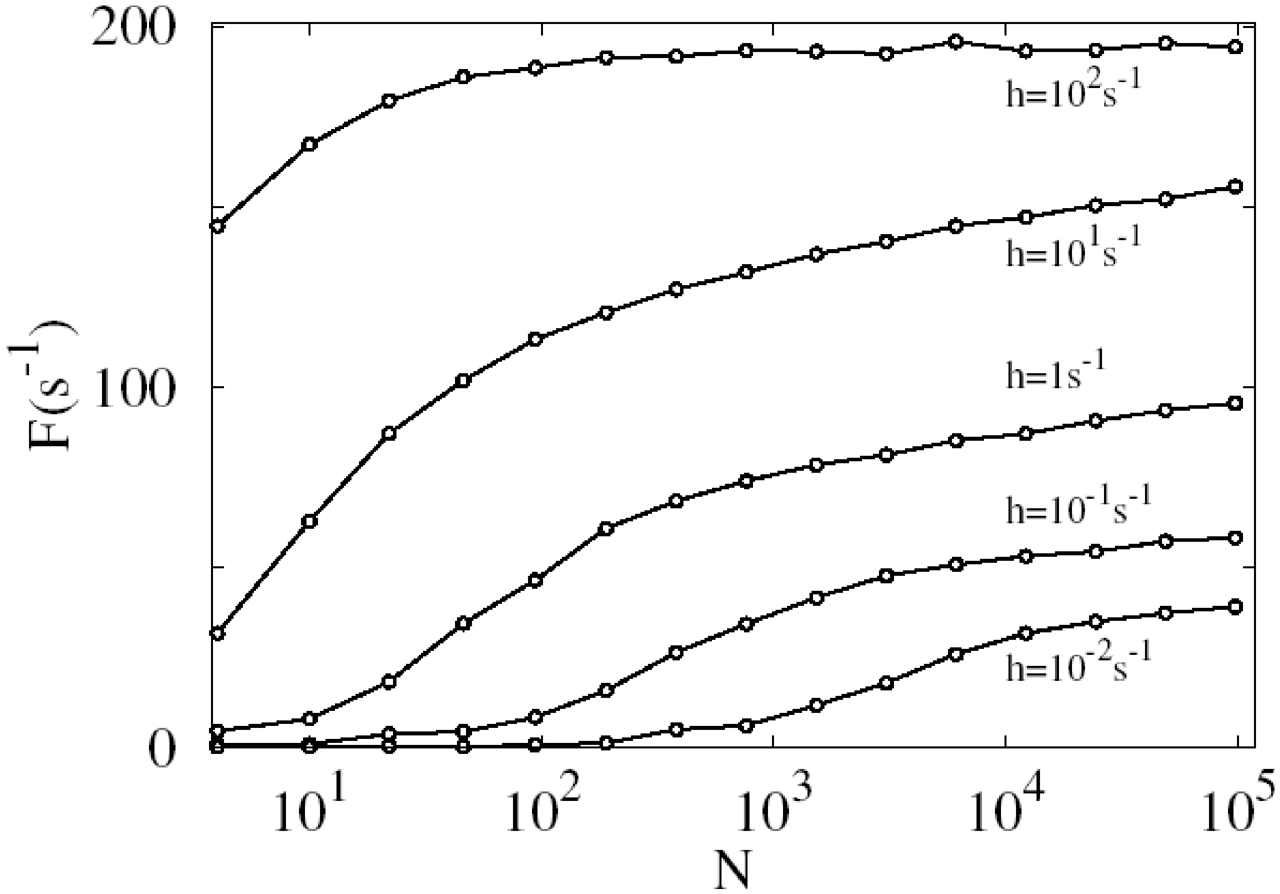

t=5 ms


t=6 ms


t=7 ms


g=2
p_λ
p_λ
p_h
p_h
p_λ
p_λ
g=1
p_h
g=0

Does the output depend on the number of branchlets?

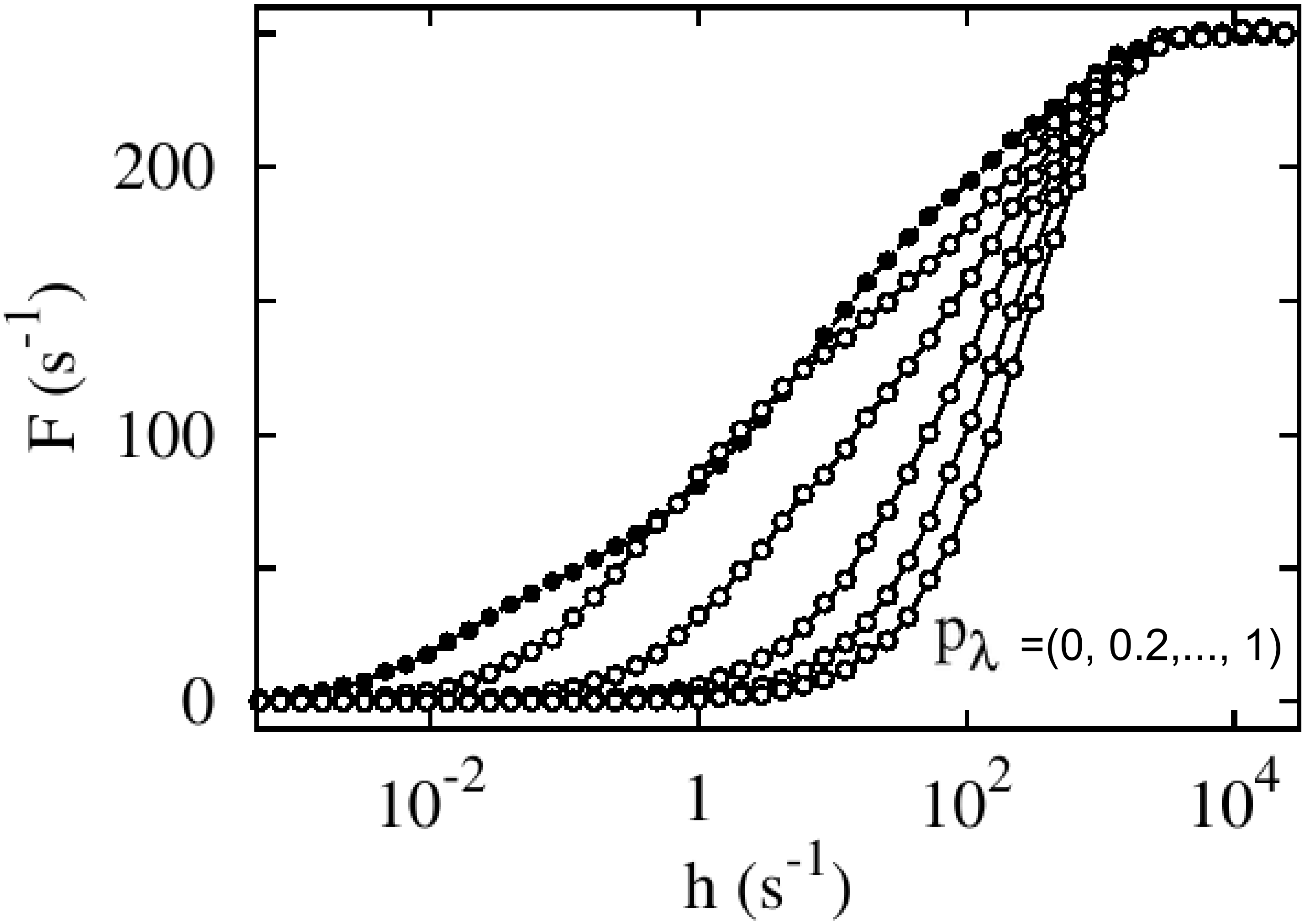


G=10

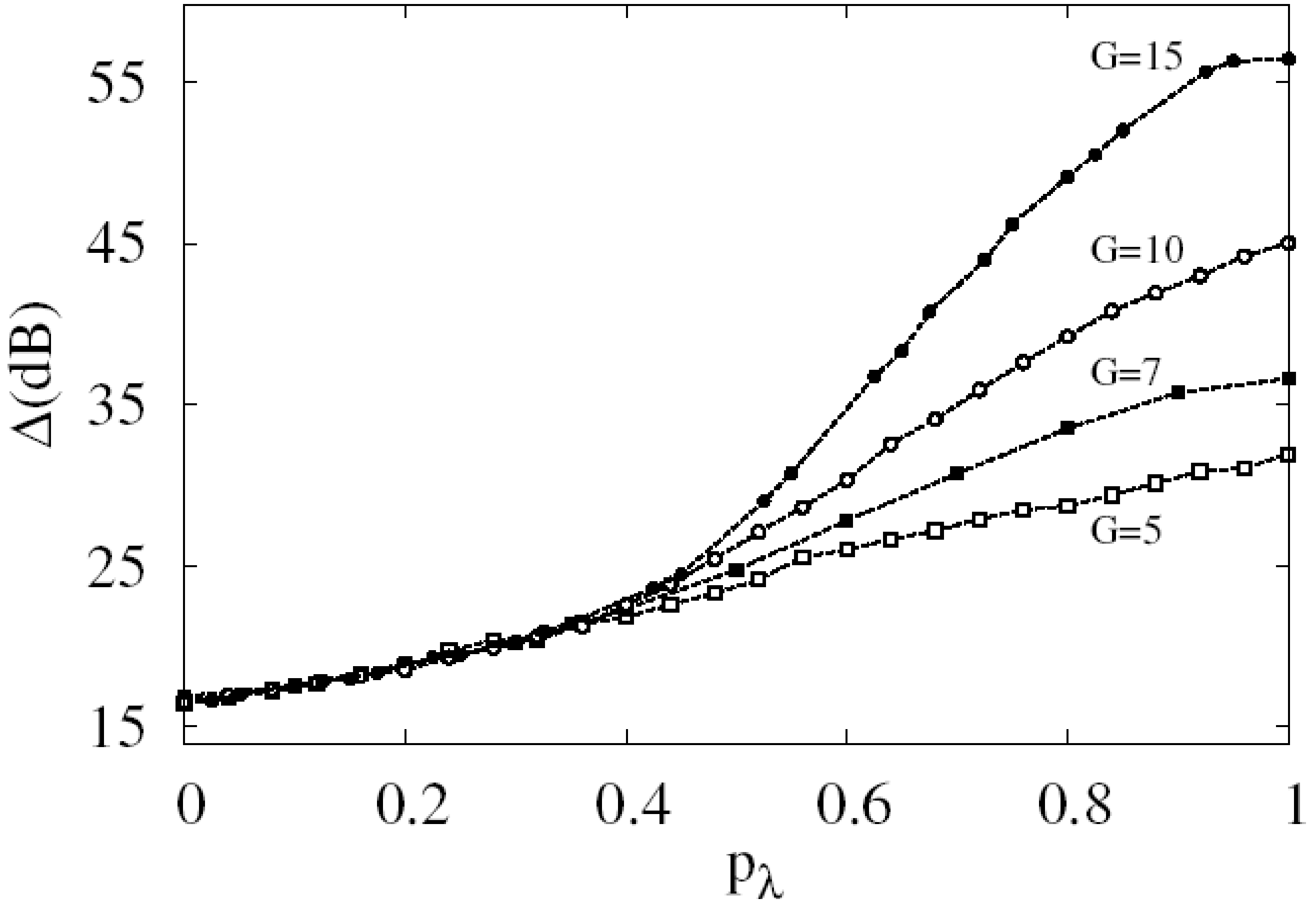
p_λ=1.0

Gollo, Kinouchi, Copelli (2009) PLoS Comput Biol

- Family of response functions G=10



Gollo, Kinouchi, Copelli (2009) PLoS Comput Biol



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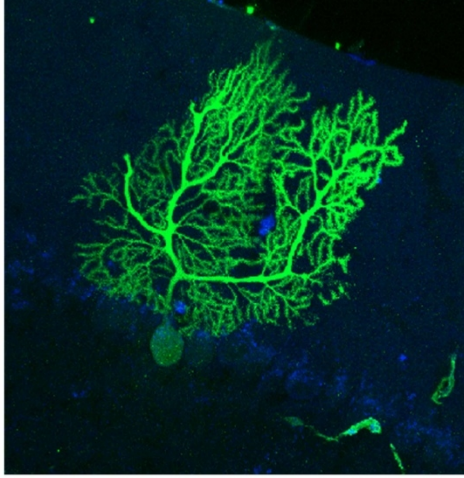
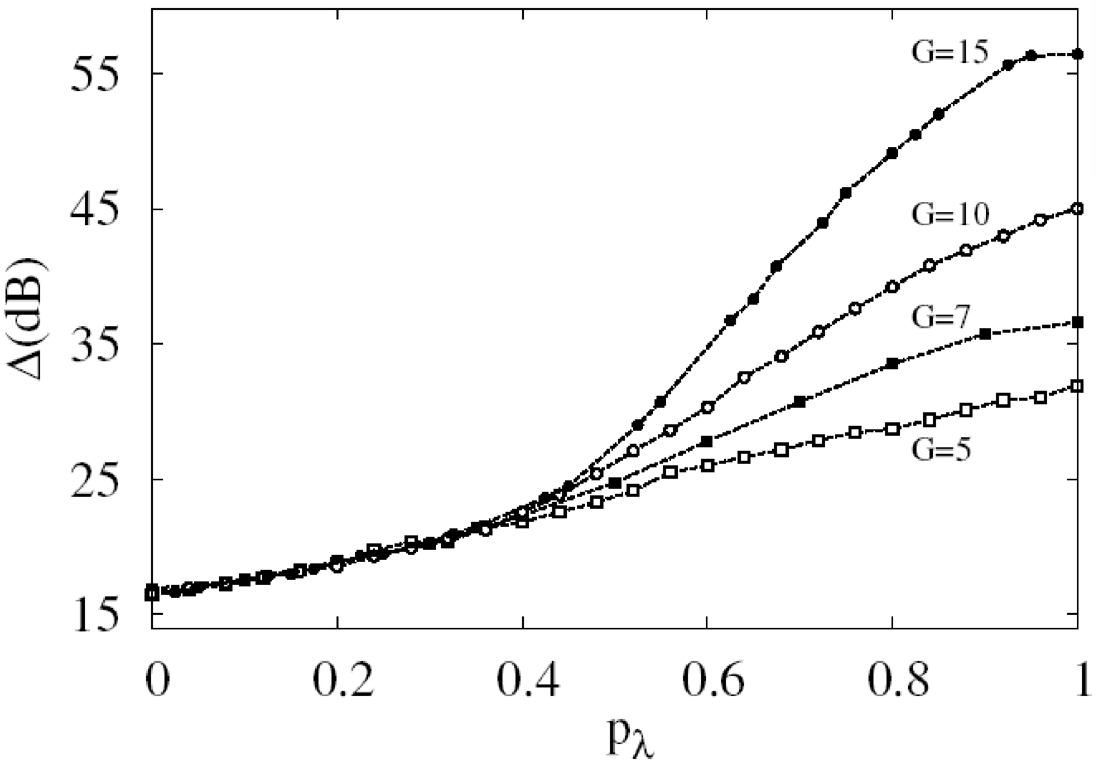
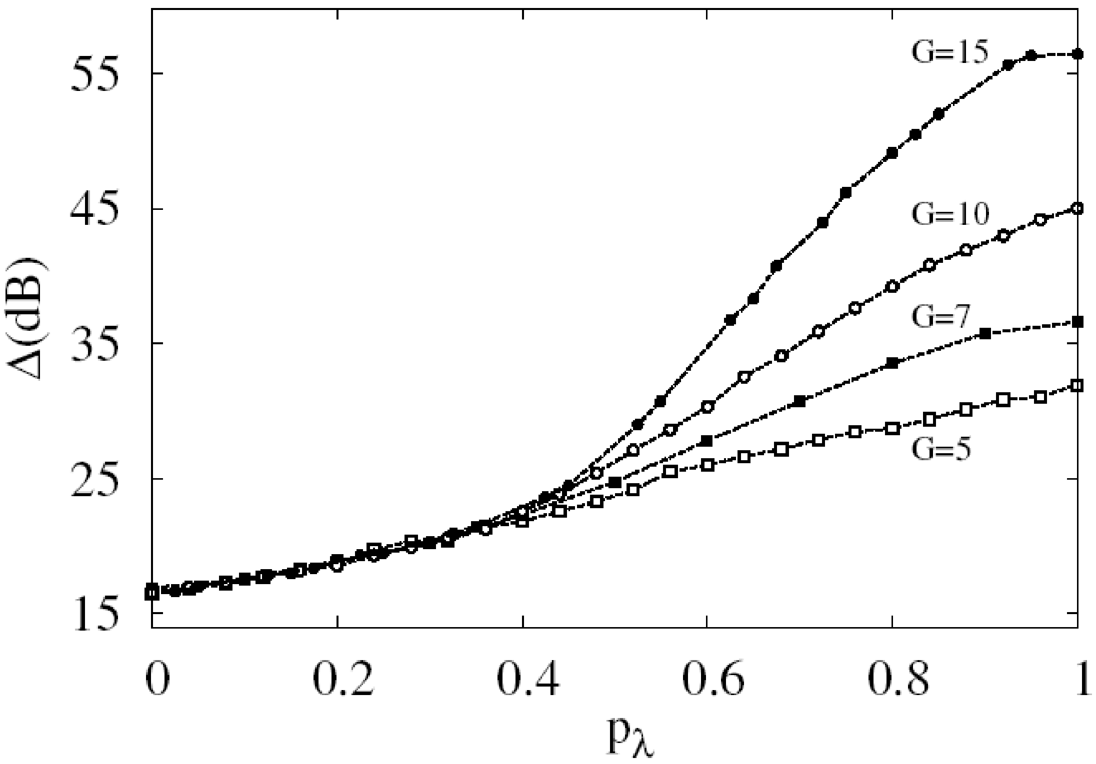




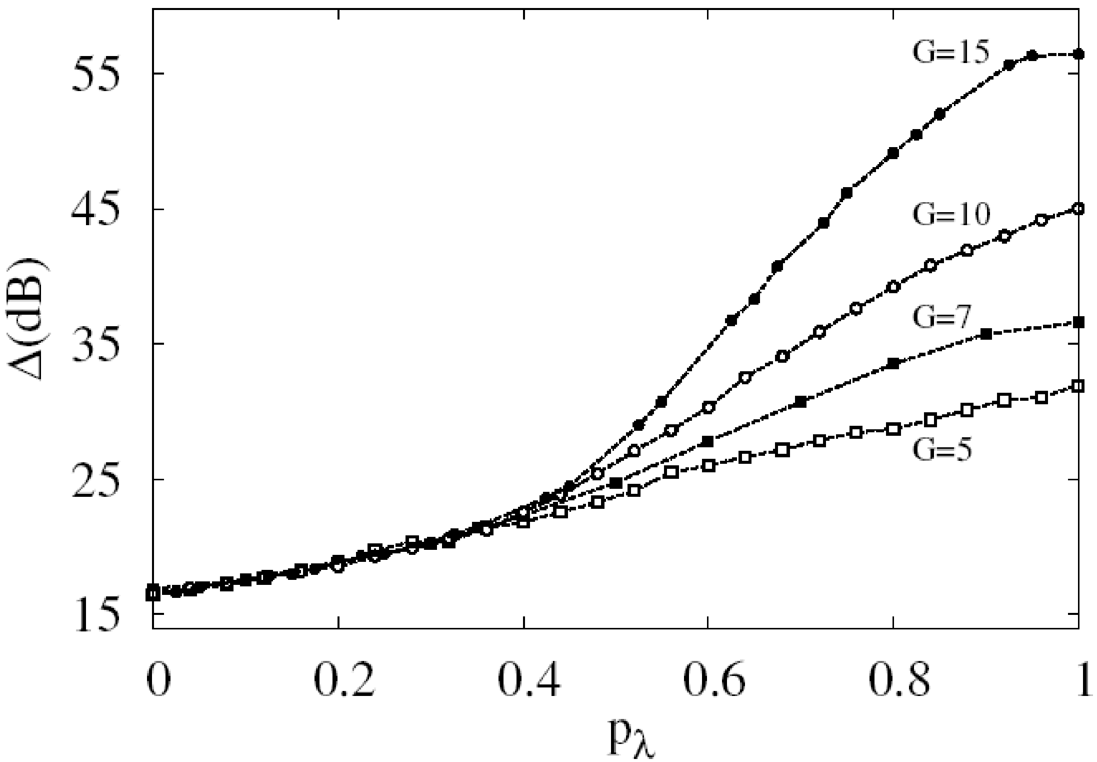
Purkinje cell Conjecture:

- play crucial role in fine motor control in cerebellum



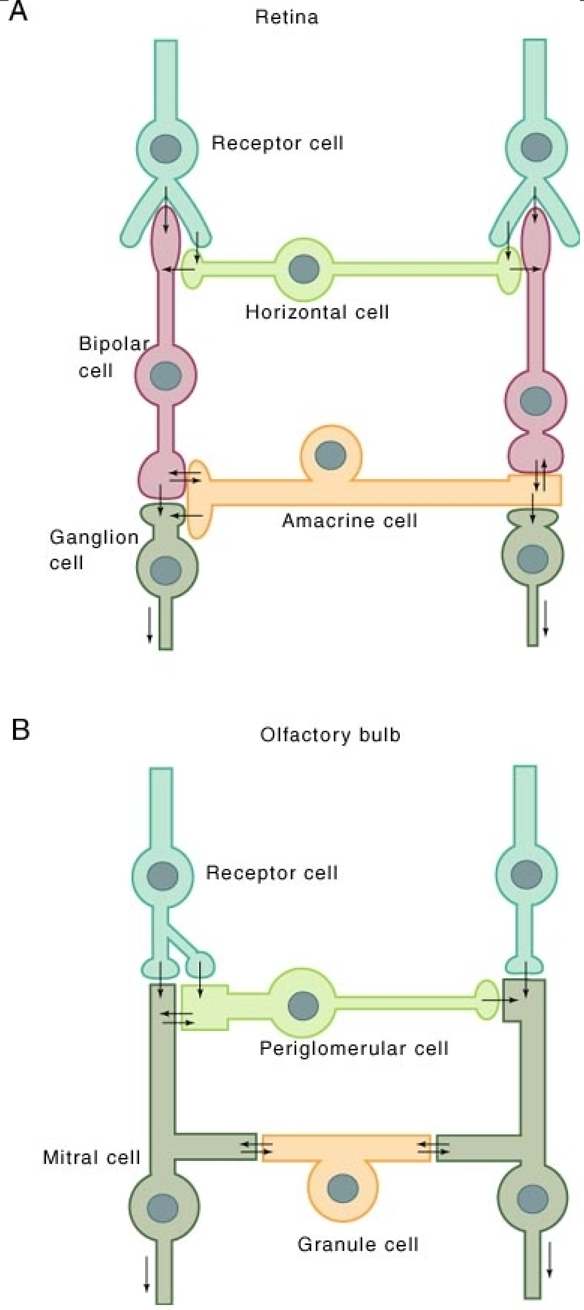
Predictions:

1. larger trees implies larger dynamic range

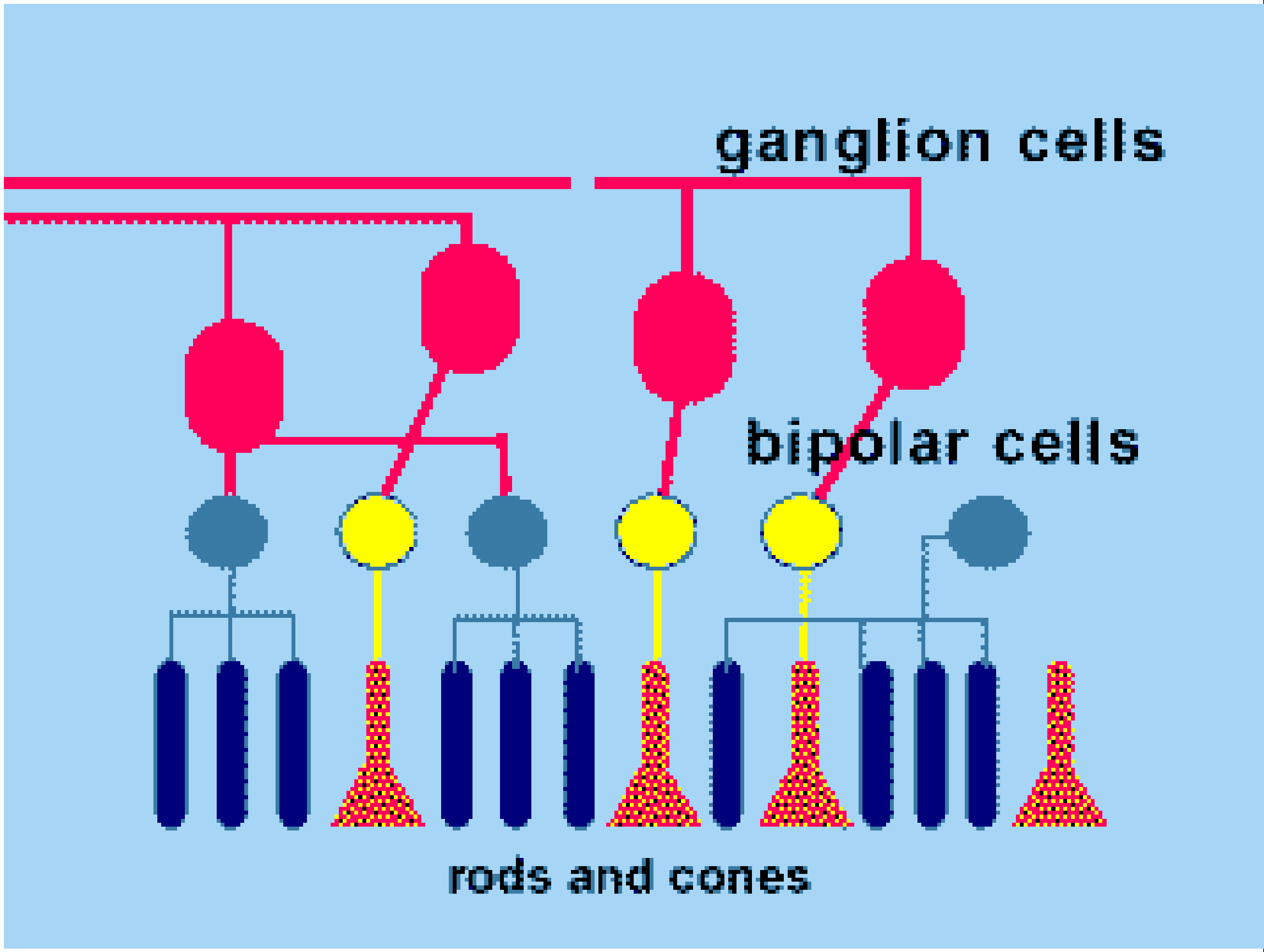


Predictions:

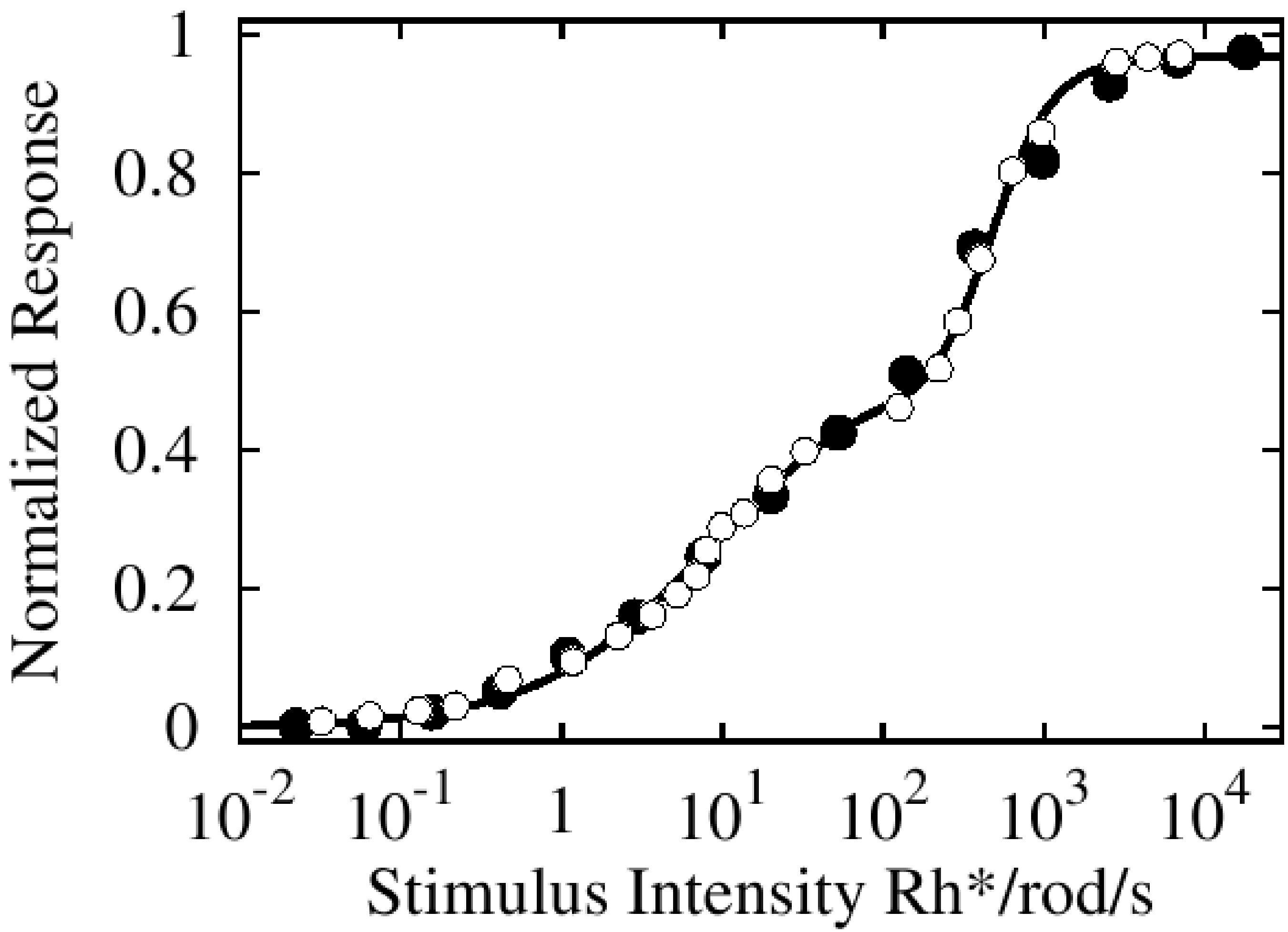
2. to block active conductances should decrease dynamic range



Shepherd 1998



- First model to obtain double sigmoid response function



- Large dendrites ⟶ low stimulus intensity

- Large dendrites -> low stimulus intensity
- Double sigmoid

- Large dendrites -> low stimulus intensity

- Double sigmoid

- dynamic range
    i. Larger and more active trees distinguish better

- Large dendrites -> low stimulus intensity

- Double sigmoid

- dynamic range
  i. Larger and more active trees distinguish better
  ii. Blocking active conductances decreases dynamic range

- Large dendrites -> low stimulus intensity

- Double sigmoid

- dynamic range
  i. Larger and more active trees distinguish better
  ii. Blocking active conductances decreases dynamic range

- Backpropagation (plasticity,memory, learn) an exaptation

New propose for active dendrites

Robust

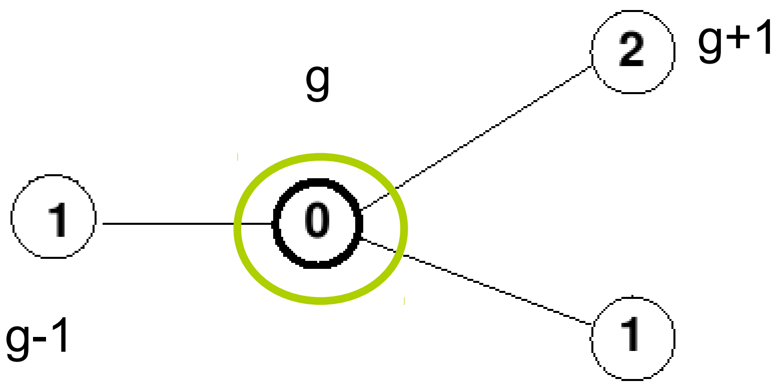
New propose for active dendrites

Robust

General properties of excitable media

- Sensory stimulus intensity problem
- Stochastic model
- Mathematical formulation

$$\overset{g}{P}(1;0;2,1) \doteq$$



$$P^{g}_{t+1}(;1;) = P^{g}_{t}(;0;)\, p_h$$

$$+(1-p_\delta)P^{g}_{t}(;1;)\,, \quad (1)$$

$$P^{g}_{t+1}(;0;) = 1 - P^{g}_{t+1}(;1;) - P^{g}_{t+1}(;2;)\,, \quad (2)$$

$$P^{g}_{t+1}(;2;) = p_\delta P^{g}_{t}(;1;) + (1-p_\gamma)P^{g}_{t}(;2;)\,, \quad (3)$$

1D Master Eq → Furtado, Copelli 2005

coordination number

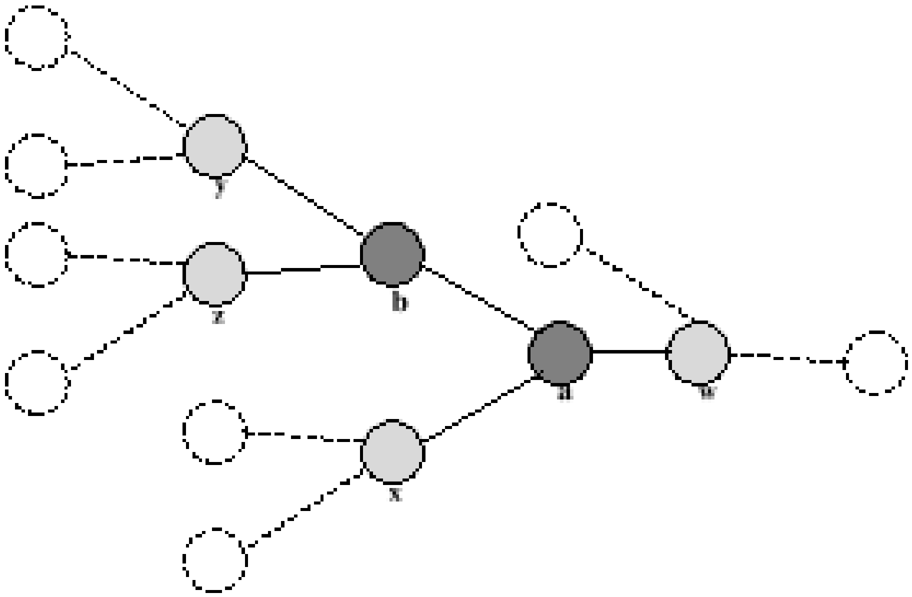
$$
\begin{aligned}
P^g_{t+1}(;1;) &= P^g_t(;0;) \\
&\quad -(1-p_h)\sum_{i=0}^{z-1}\Bigg[p^i_\lambda \binom{z-1}{i}(-1)^i P^g_t\left(;0;1^{(i)}\right) \\
&\quad -\beta p^{i+1}_\lambda \binom{z-1}{i}(-1)^i P^g_t\left(1;0;1^{(i)}\right)\Bigg] \\
&\quad +(1-p_\delta)P^g_t(;1;)\,, && (1)\\
P^g_{t+1}(;0;) &= 1 - P^g_{t+1}(;1;) - P^g_{t+1}(;2;)\,, && (2)\\
P^g_{t+1}(;2;) &= p_\delta P^g_t(;1;) + (1-p_\gamma)P^g_t(;2;)\,, && (3)
\end{aligned}
$$

$$P_t(j_1 \,|j_2, \ldots, j_m) \approx P_t(j_1)\,,$$

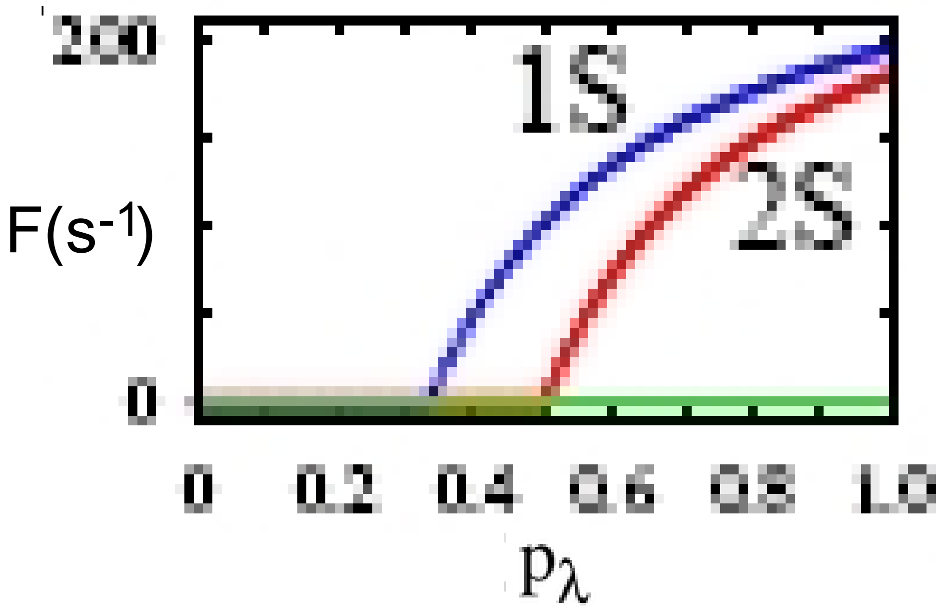
$$\Longrightarrow P_t(j_1; j_2, \ldots, j_{m-1}, j_m) \approx \prod_{i=1}^{m} P_t(j_i)\,.$$

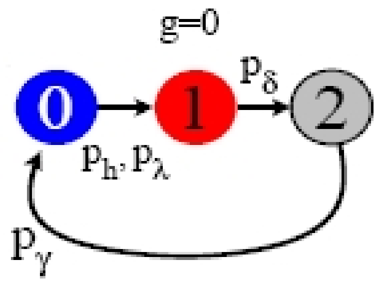
$$P_t(j_1 | j_2, \ldots, j_m) \approx P_t(j_1 | j_2) \, ,$$

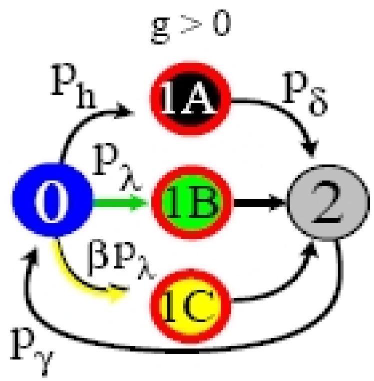
$$\Longrightarrow P_t(j_1 ; j_2, \ldots, j_{m-1}, j_m) \approx \frac{P_t(j_1, j_2) P_t(j_2, j_3) \ldots P_t(j_{m-1}, j_m)}{P_t(j_2) \ldots P_t(j_{m-1})} \, .$$

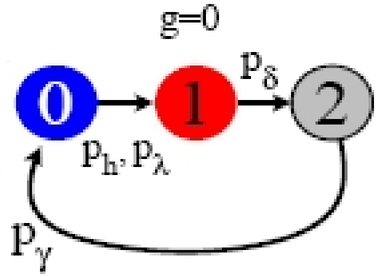


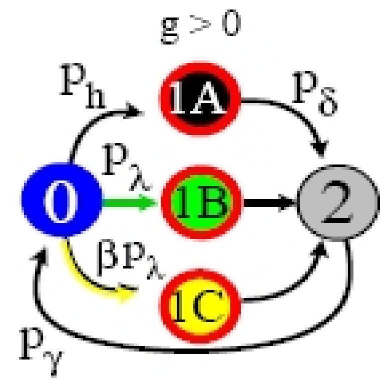
h=0

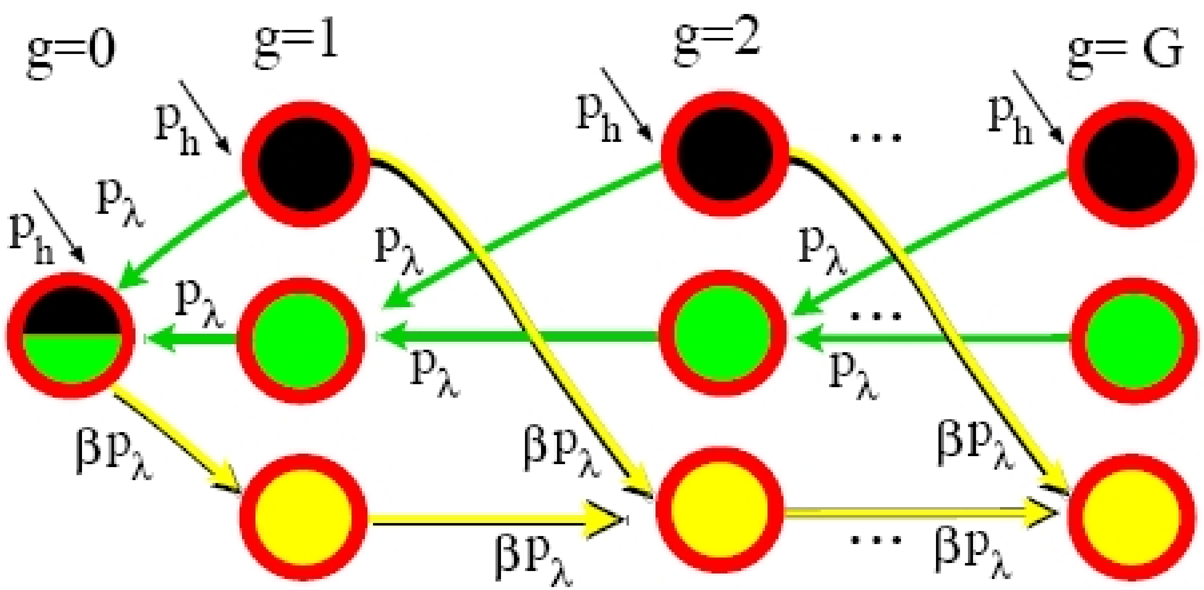



g=0
0
1
2
p_δ
p_h, p_λ
p_γ

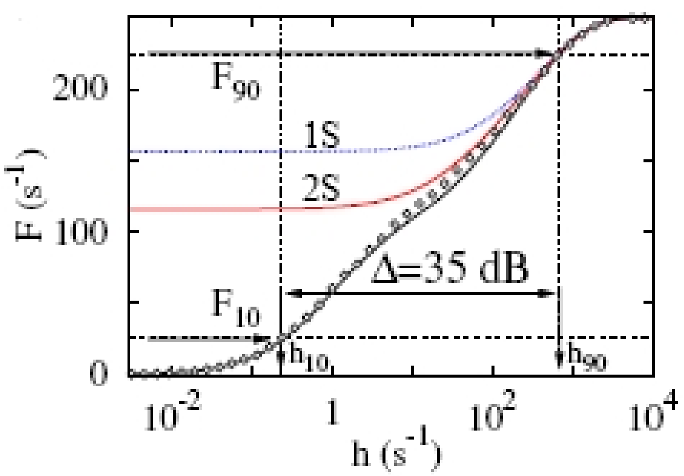

g > 0
0
1A
1B
1C
2
p_h
p_δ
p_λ
βp_λ
p_γ







Gollo, Copelli (in prep.)



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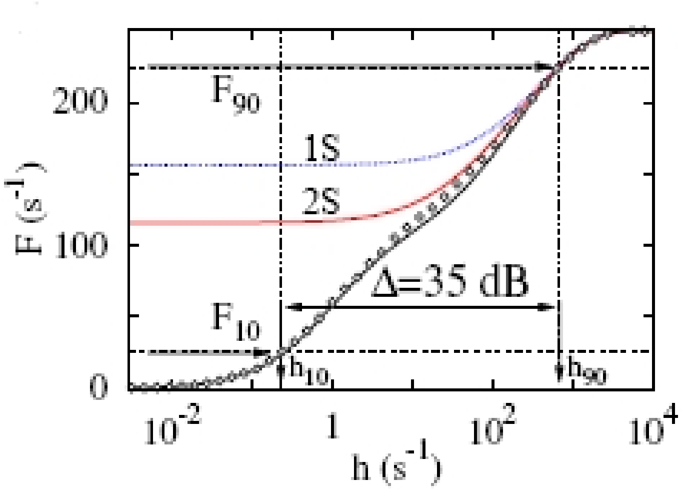
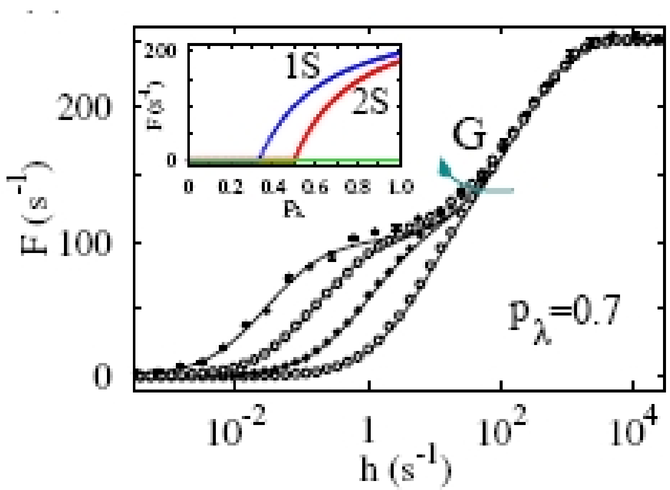
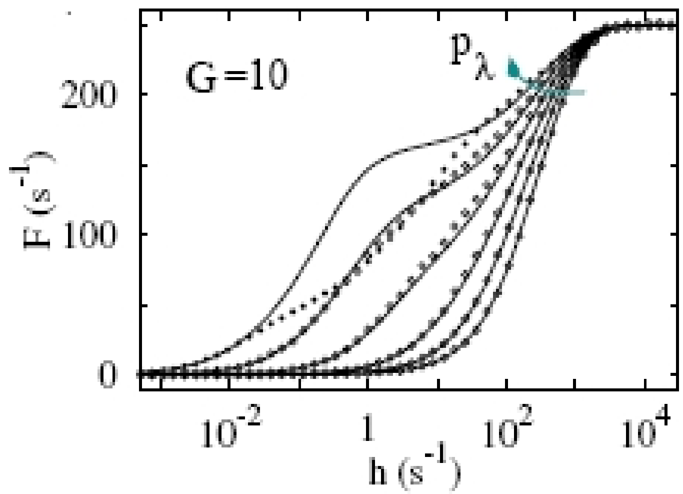
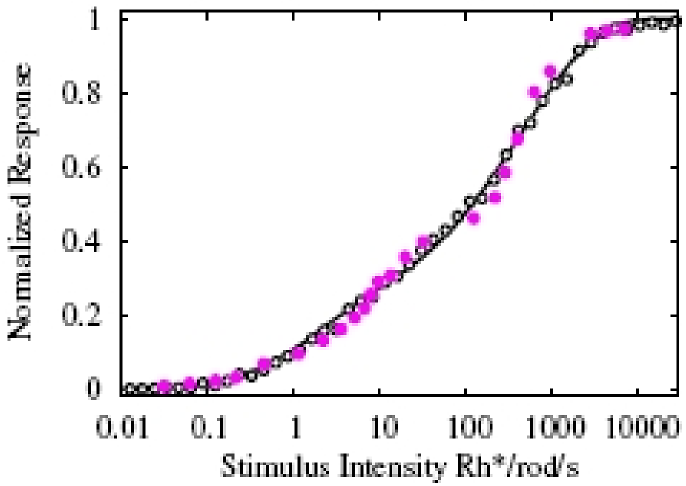




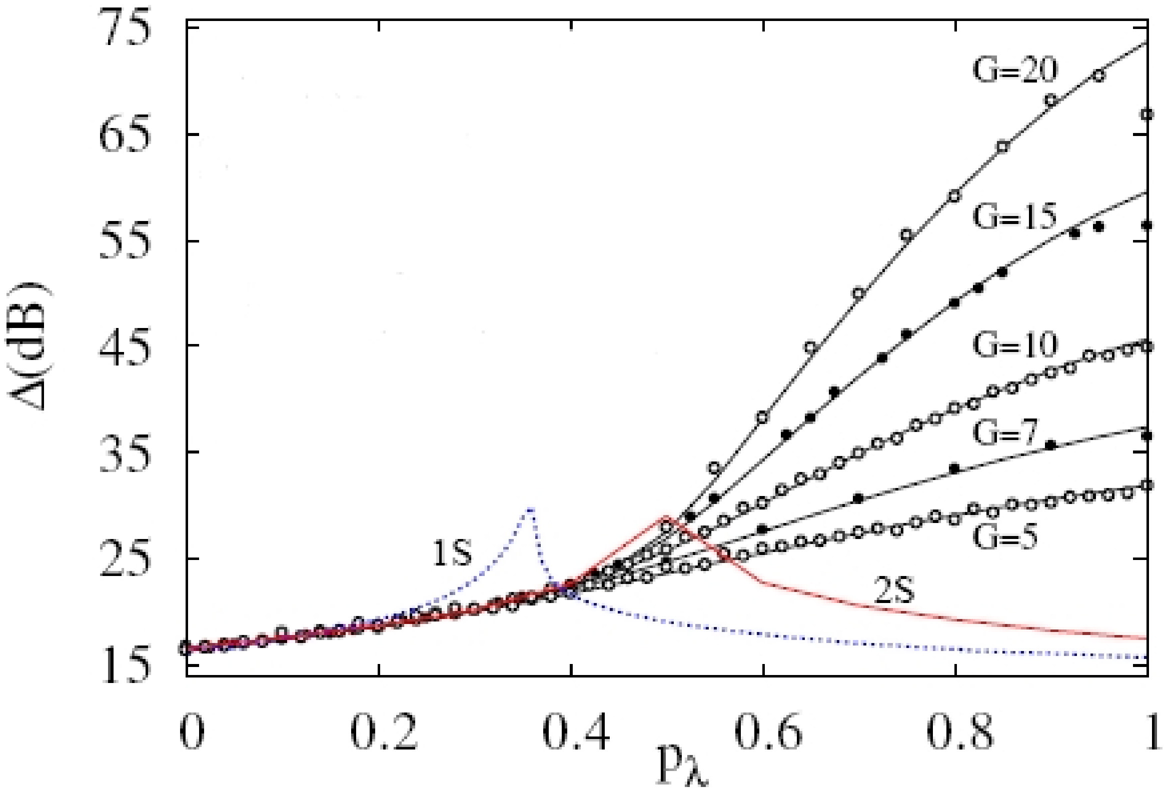
Gollo, Copelli (in prep.)



Deans et al. Neuron 2002



Gollo, Copelli (in prep.)



Gollo, Copelli (in prep.)

Final remark : EW

Captures essential dynamical aspects

Good agreement: simulations and experimental data

Thank you!