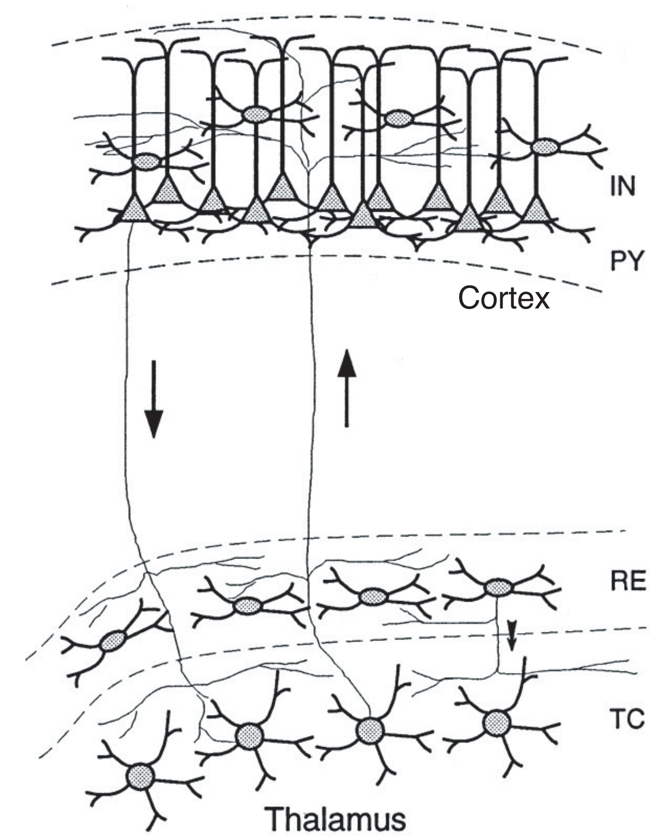
Mathematical Neuroscience: from neurons to networks

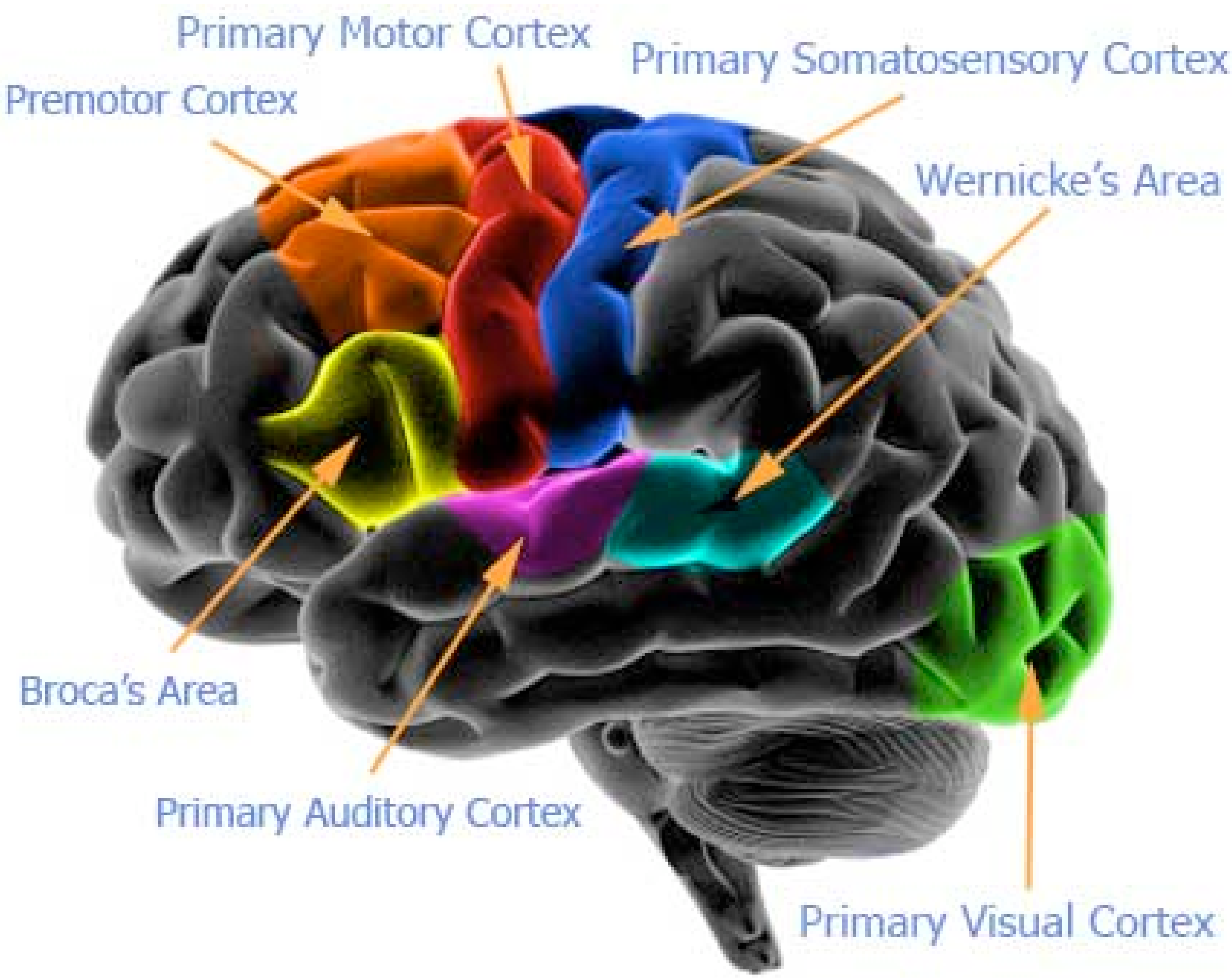
Steve Coombes

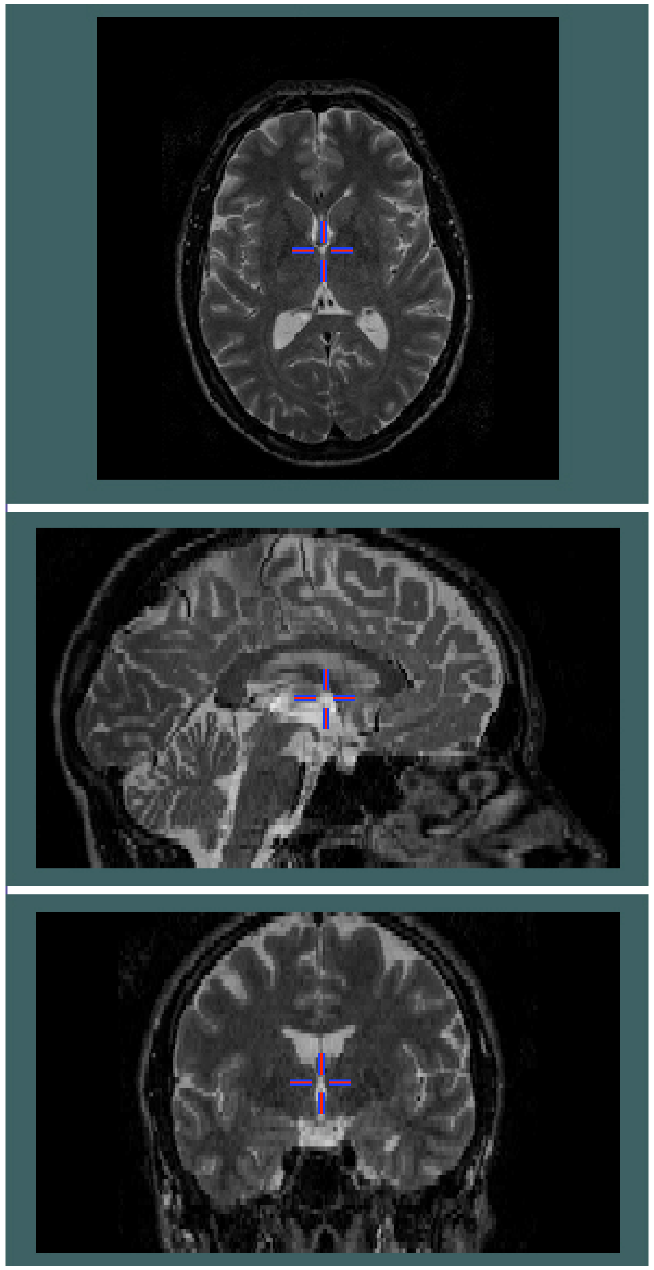


The University of Nottingham

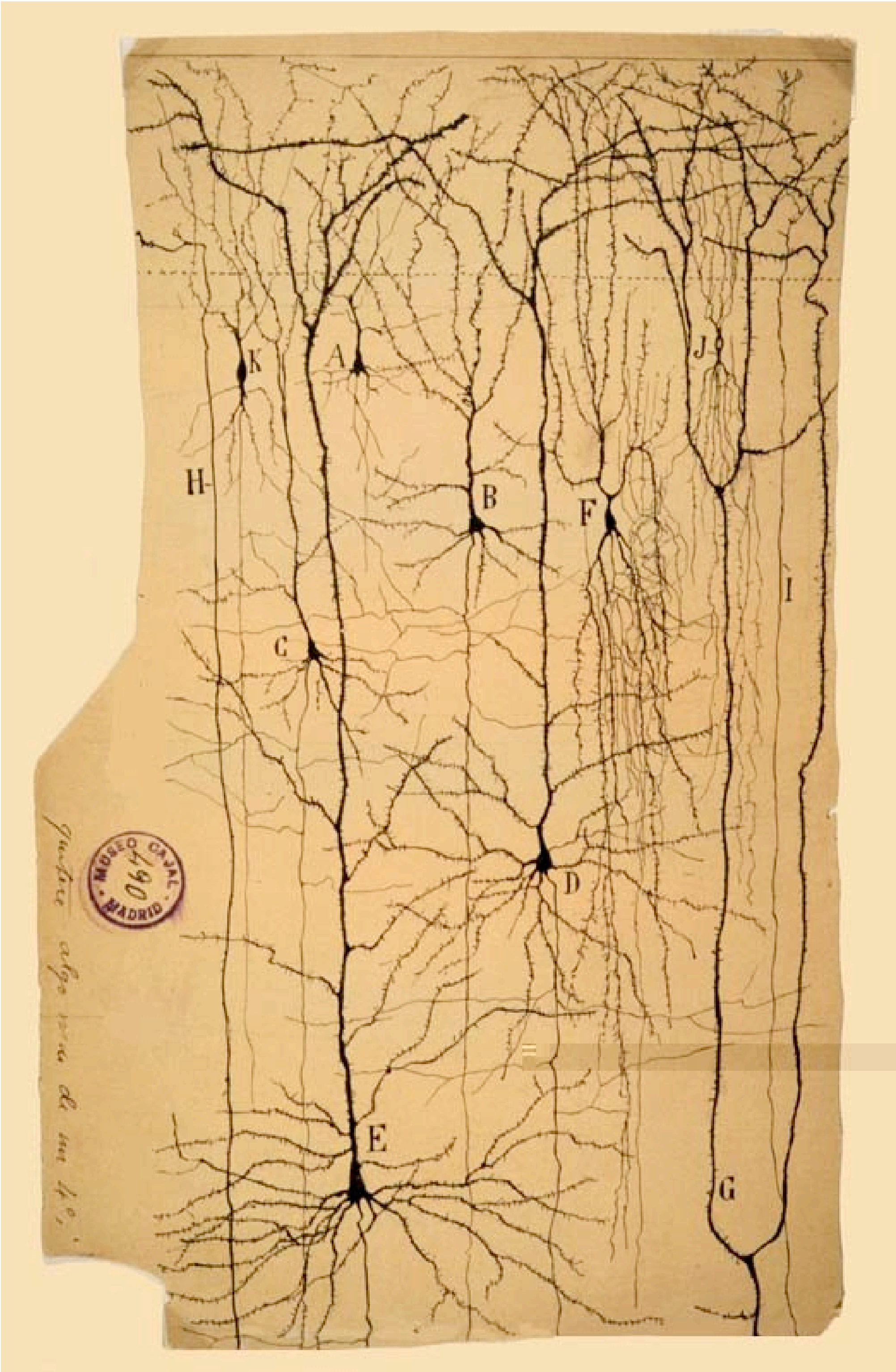
School of Mathematical Sciences

Brain and Cortex



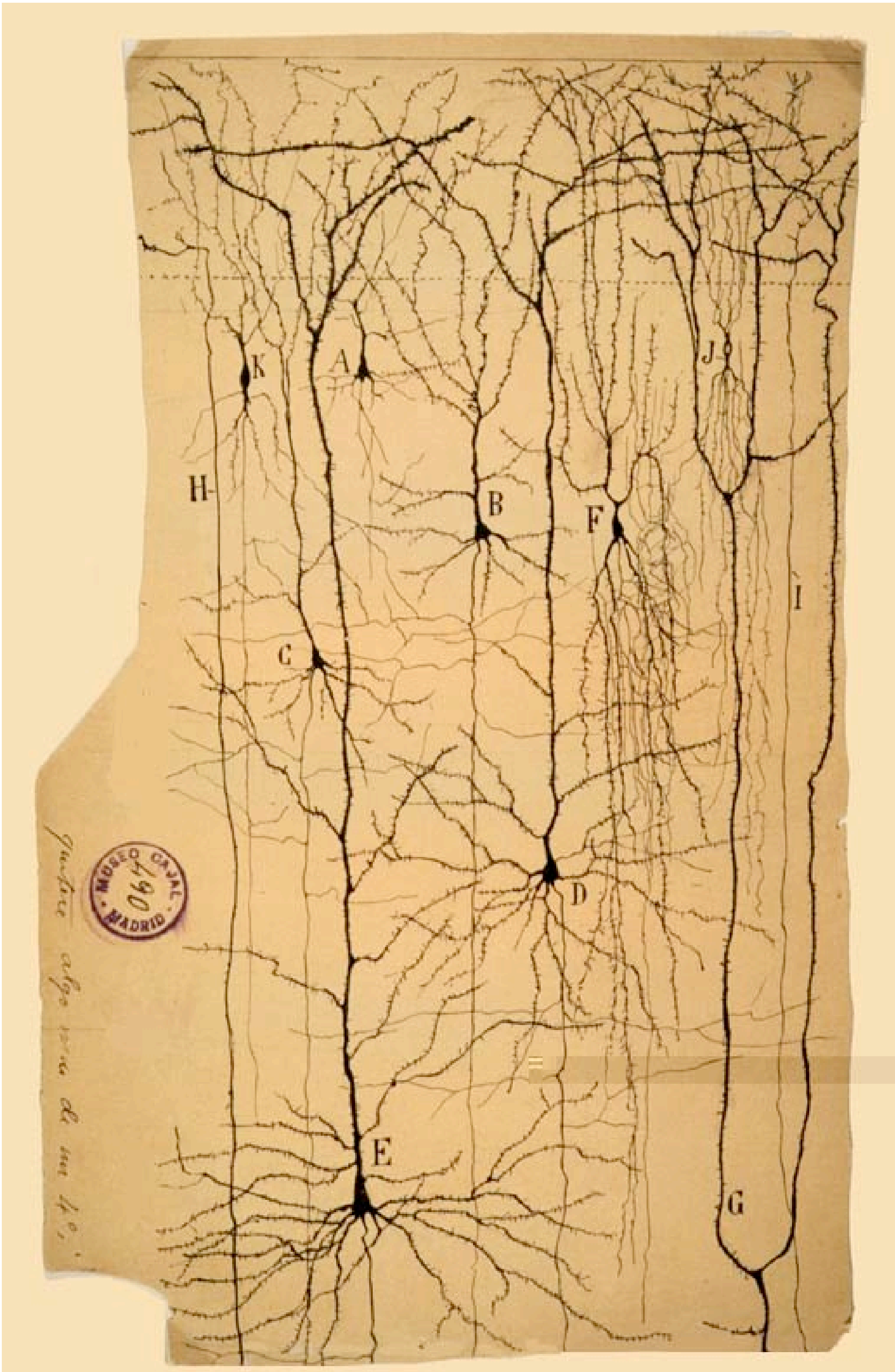


Principal cells and interneurons



Santiago Ramón y Cajal
1900

Principal cells and interneurons



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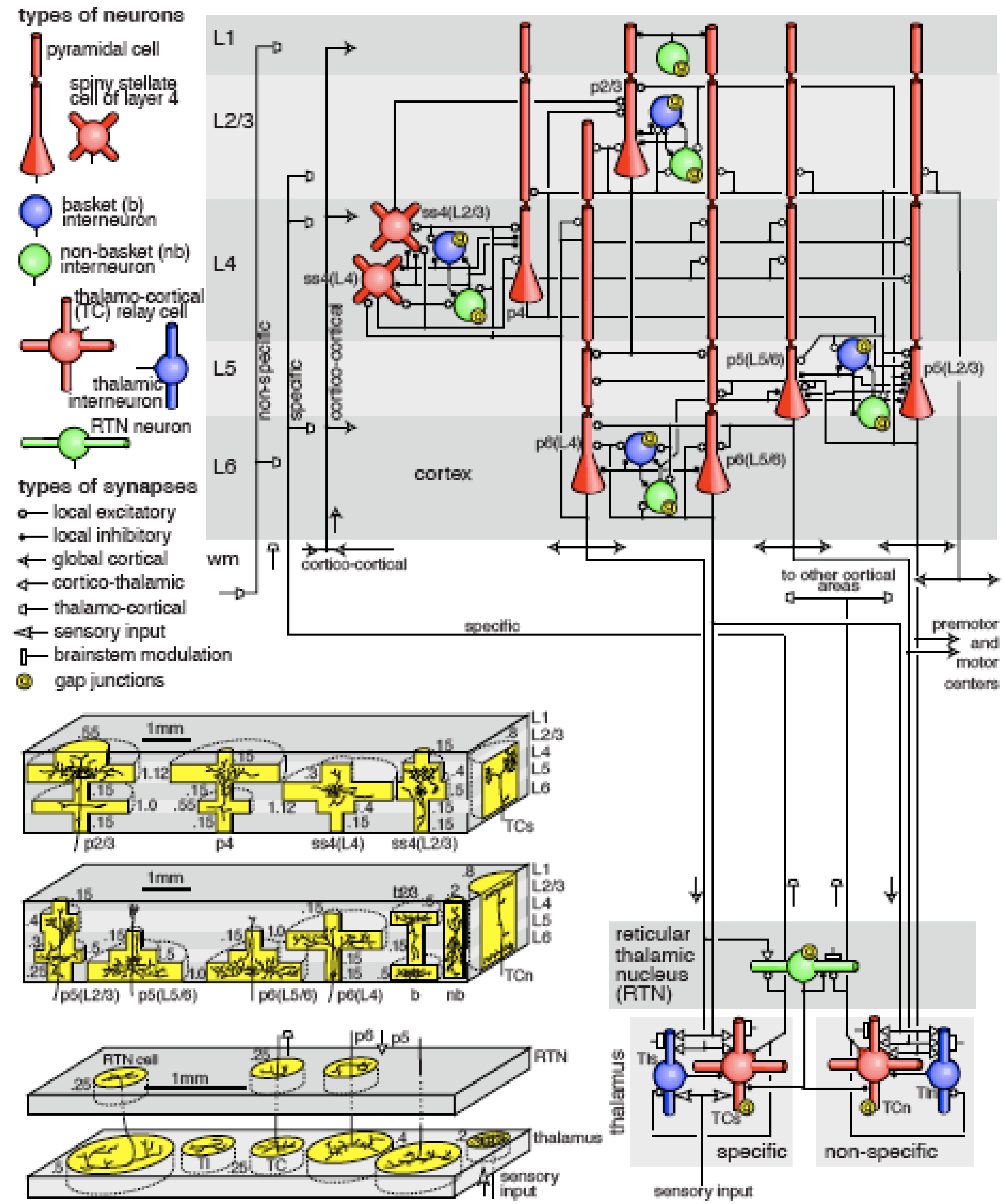
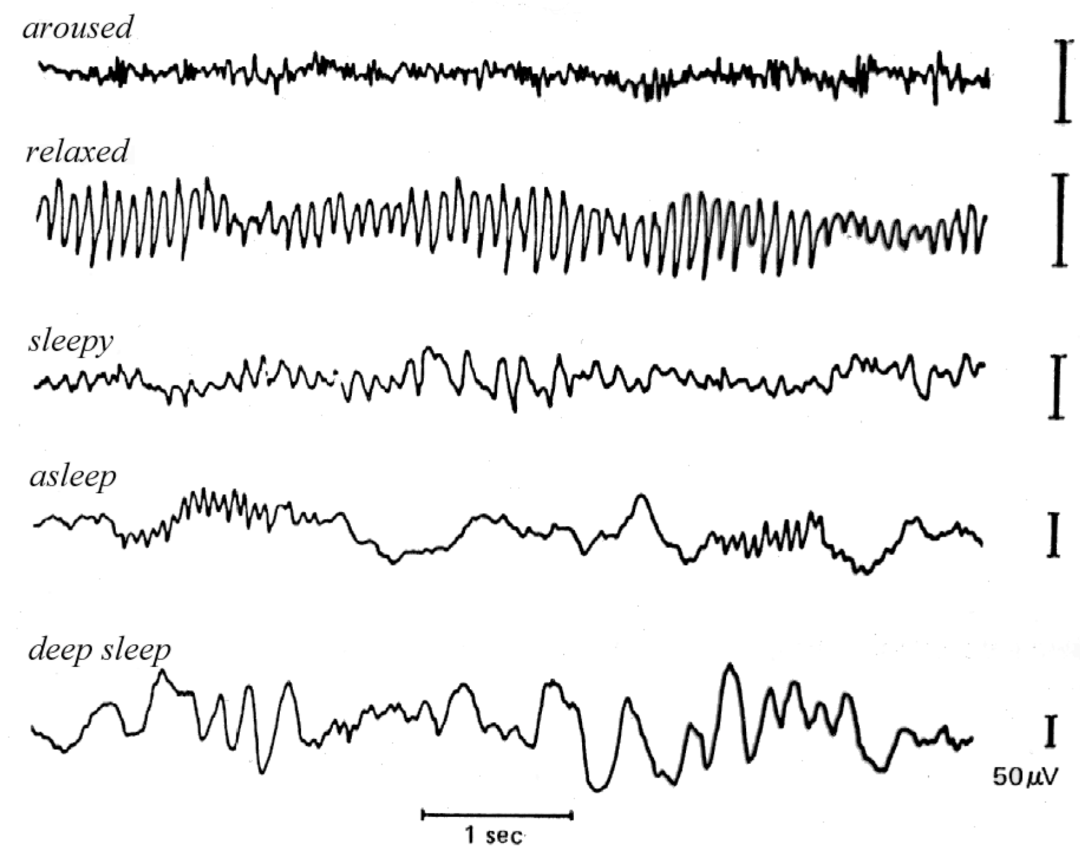


Eugene Izhikevich
2008

Electroencephalogram (EEG) power spectrum



α

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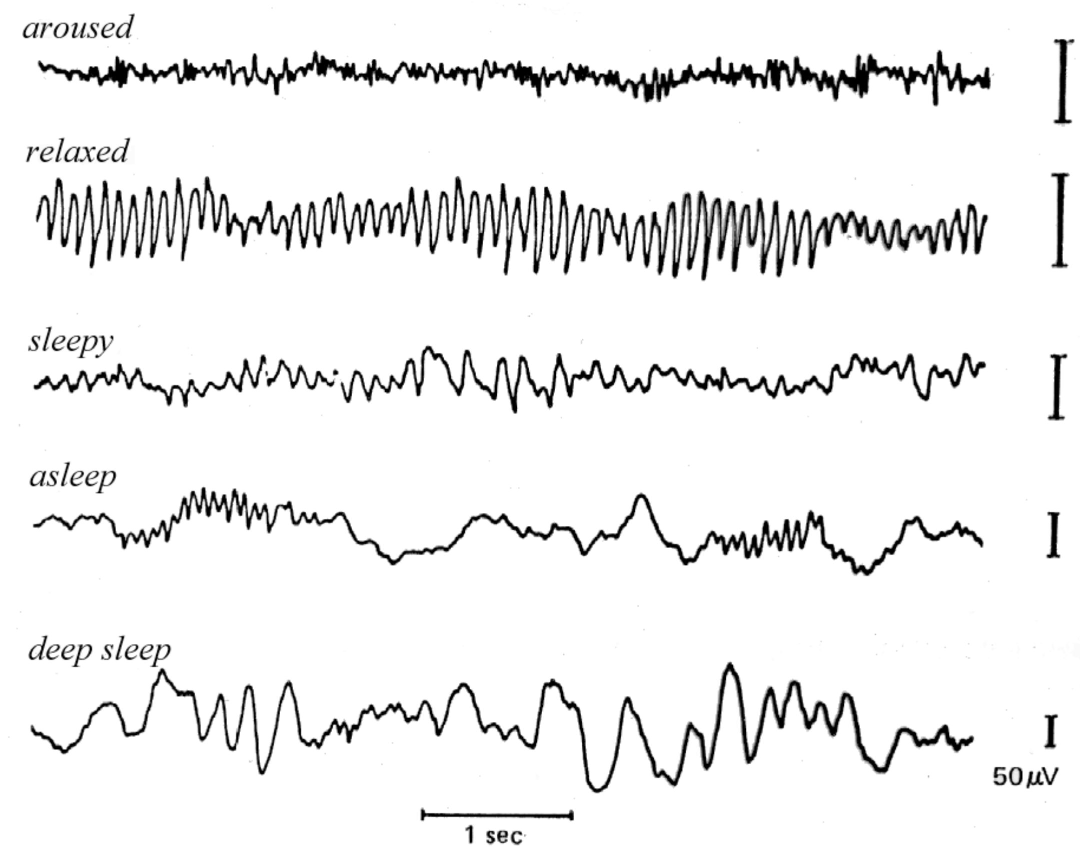
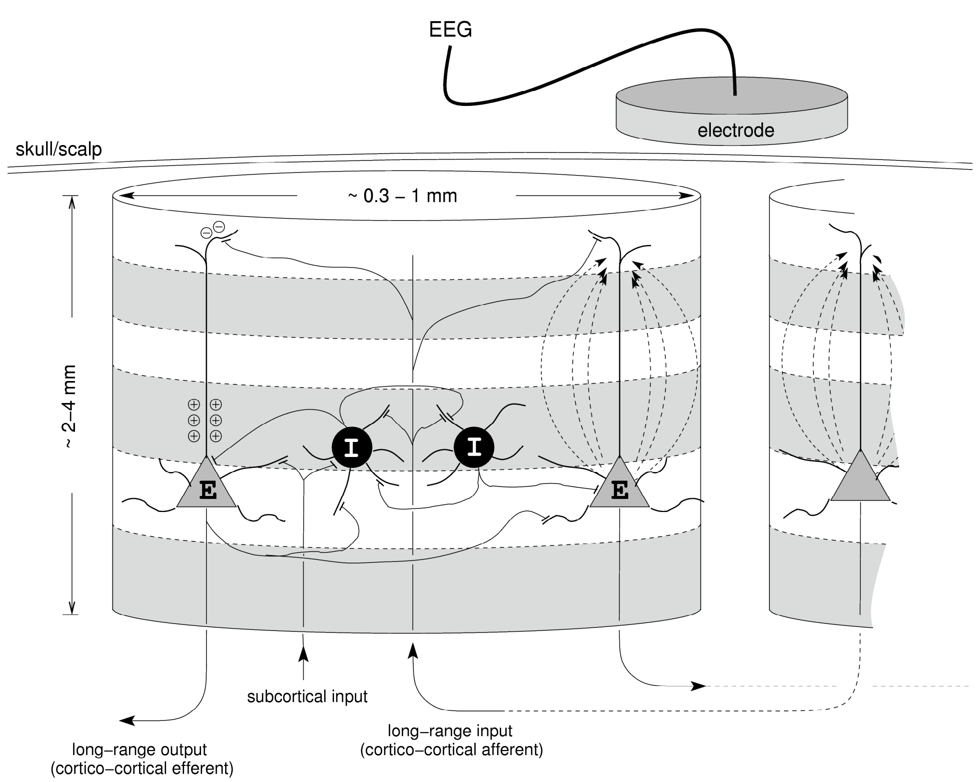
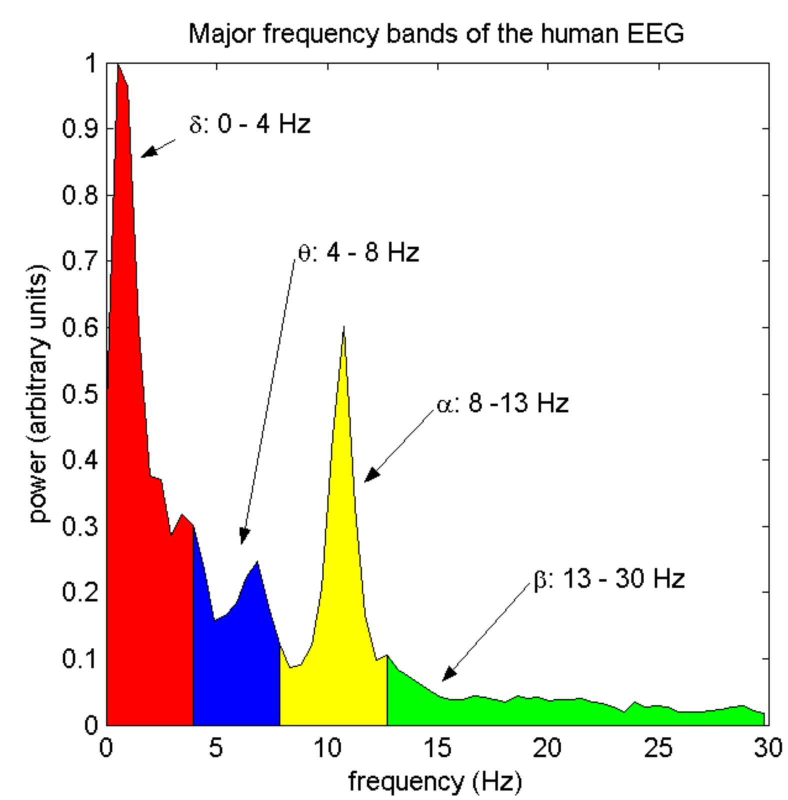


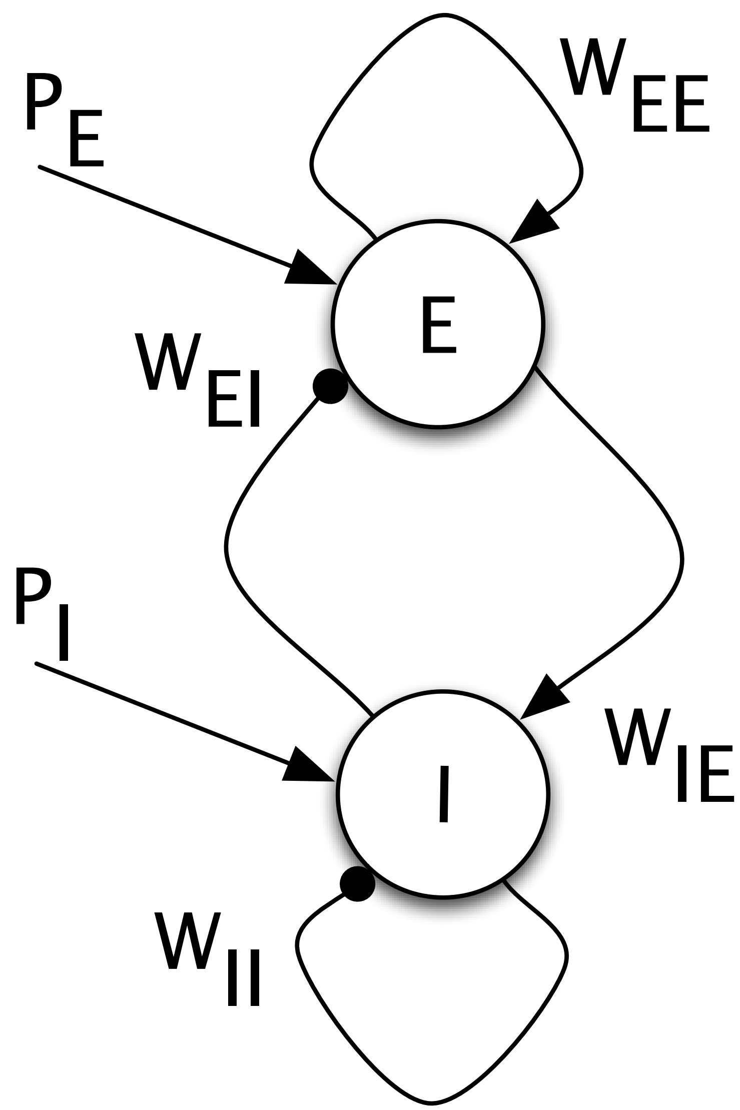
α



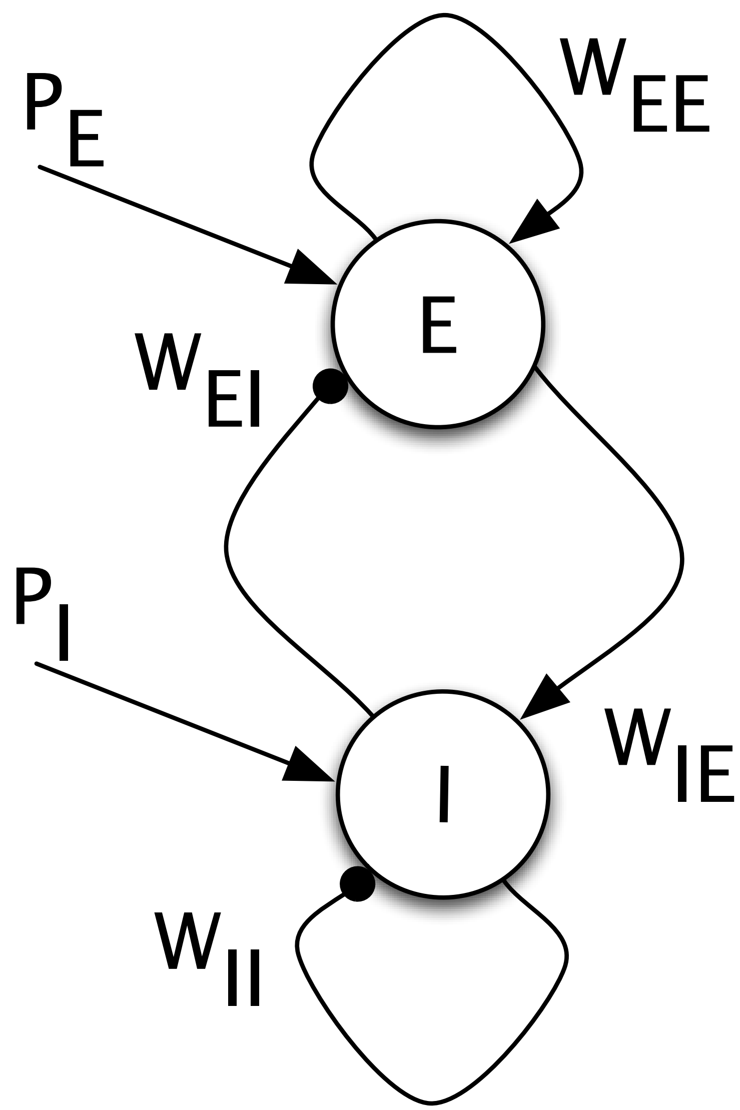


EEG records the activity of ~ 10^6 pyramidal neurons.

Population model

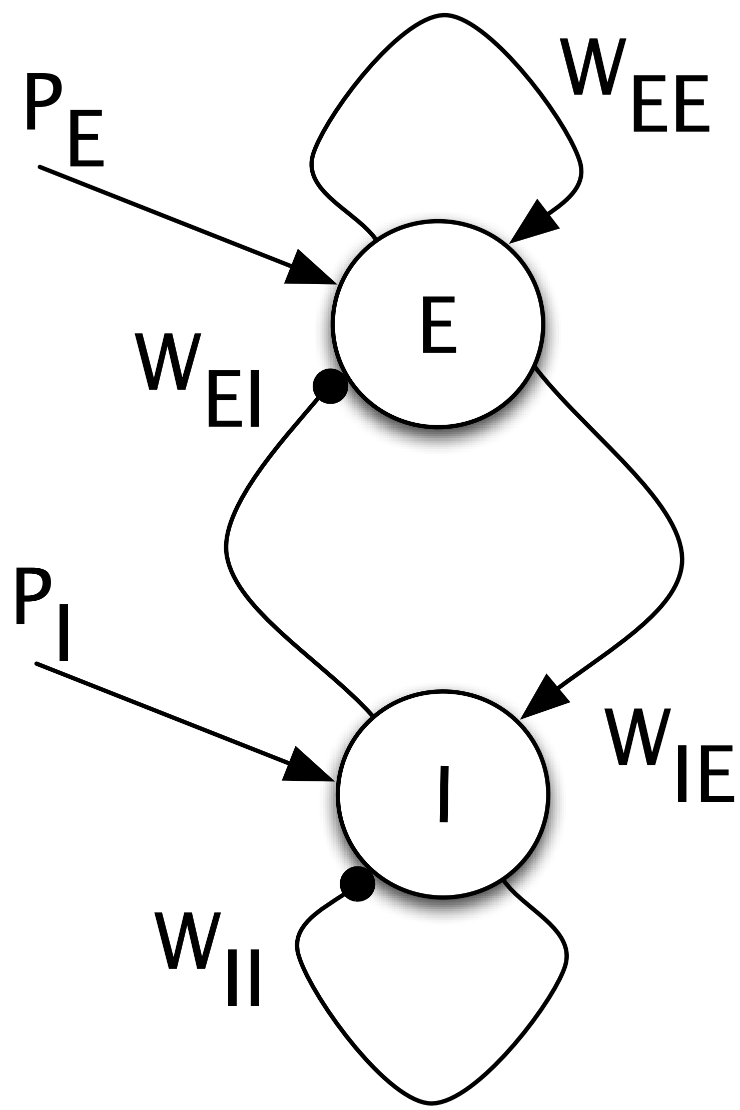


Population model

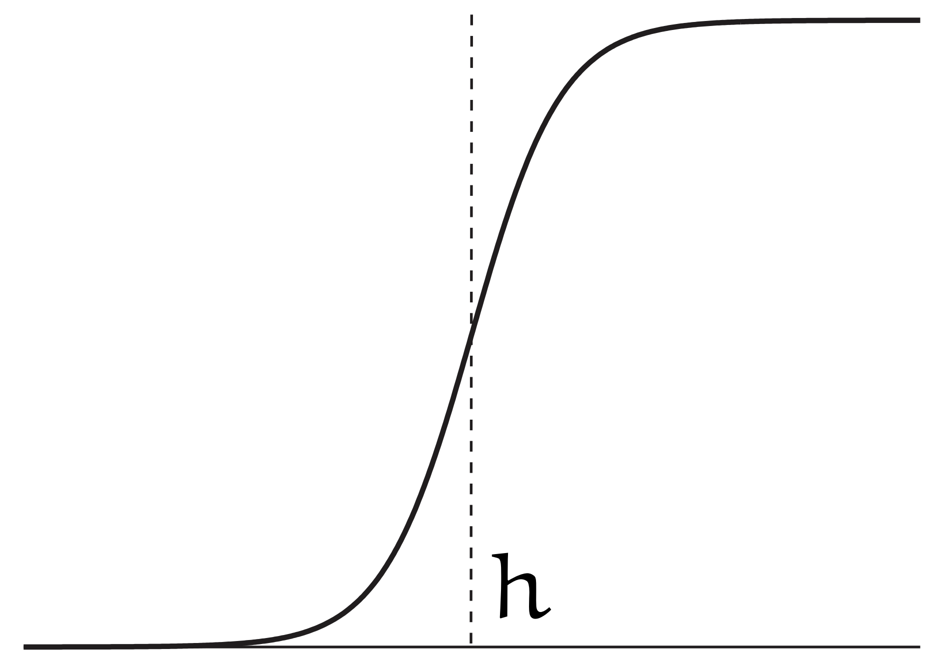


$$\dot{E} = -\frac{E}{\tau_E} + W_{EE}\, g_{EE}(A^+ - E) + W_{EI}\, g_{EI}(A^- - E) + P_E$$

Population model



Firing rate activity $f(E)$



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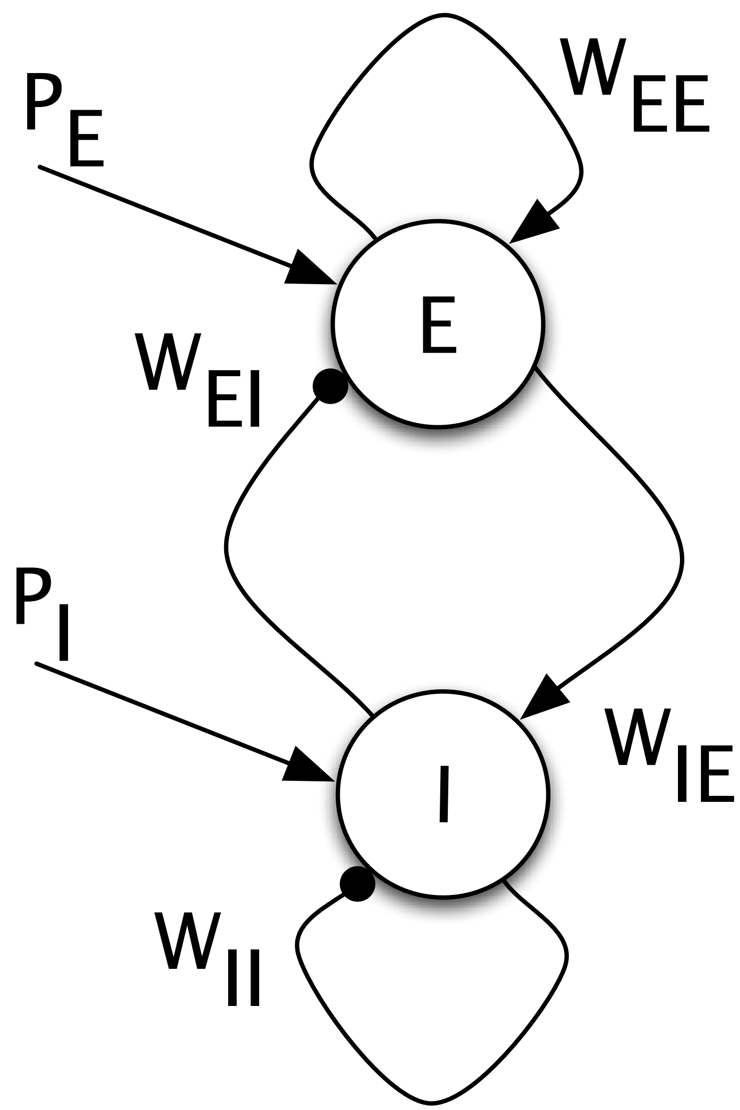

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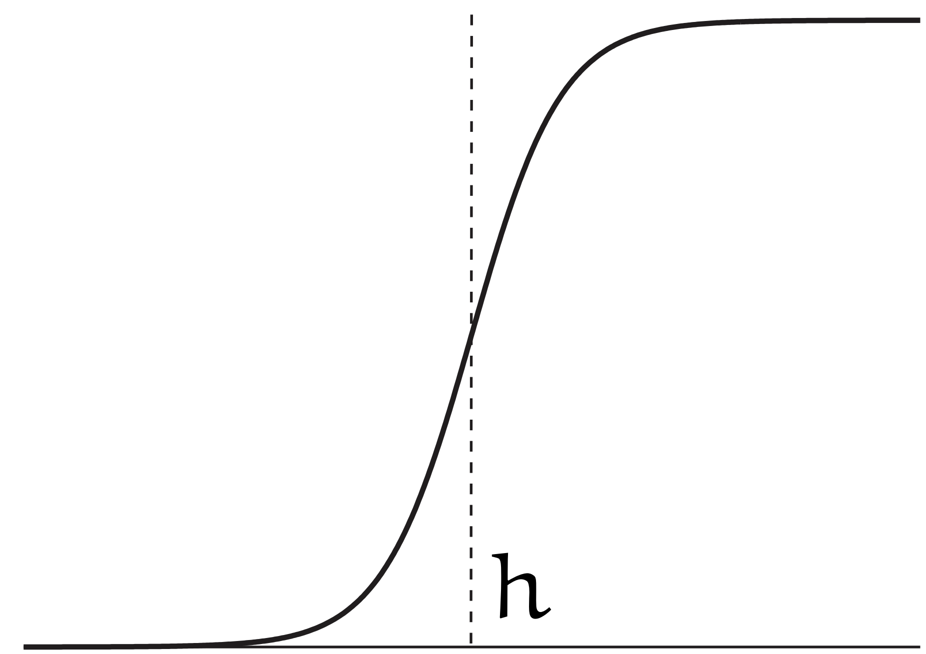
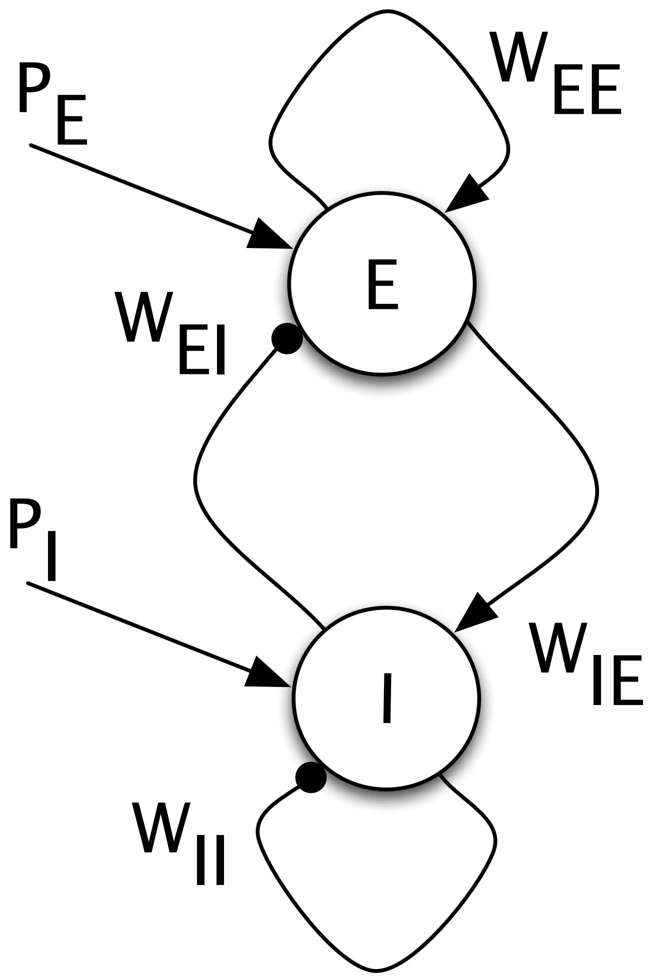


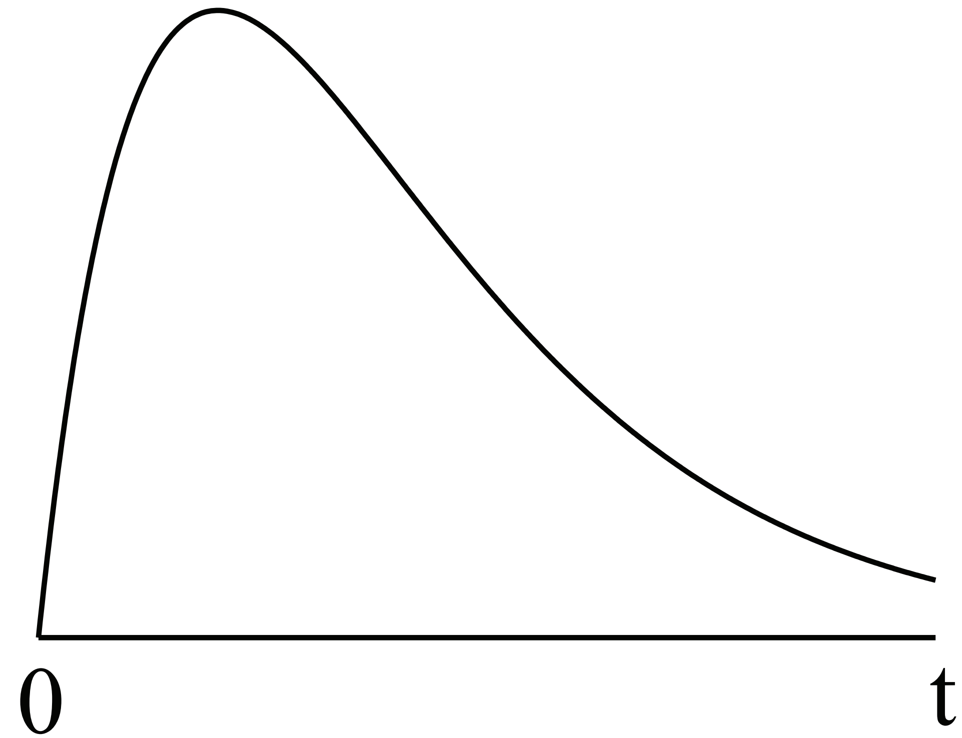
Firing rate activity $f(I)$

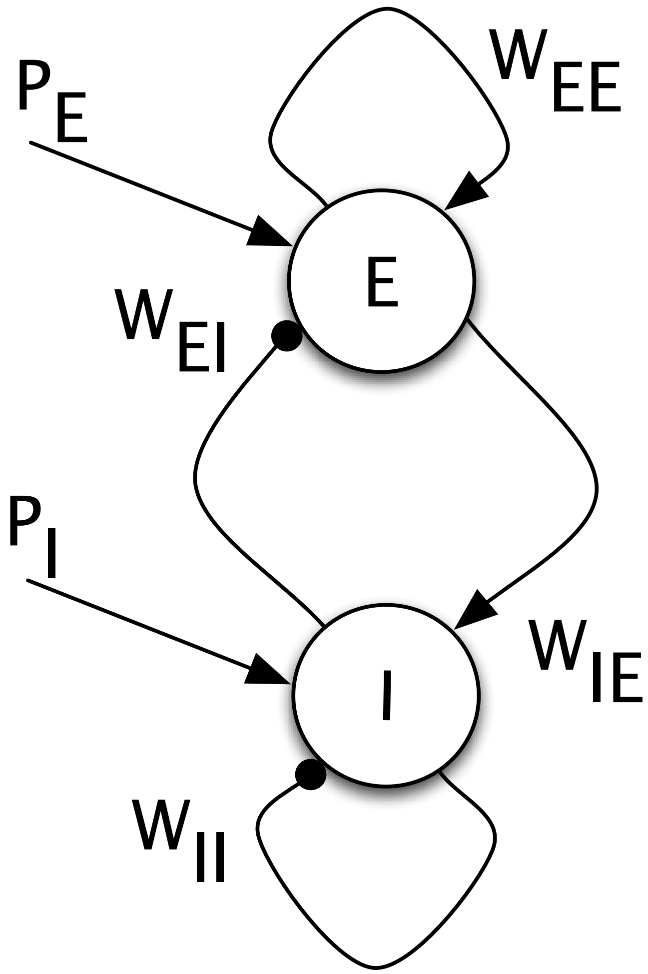
$$\dot{E} = -\frac{E}{\tau_E} + W_{EE} g_{EE}(A^+ - E) + W_{EI} g_{EI}(A^- - E) + P_E$$

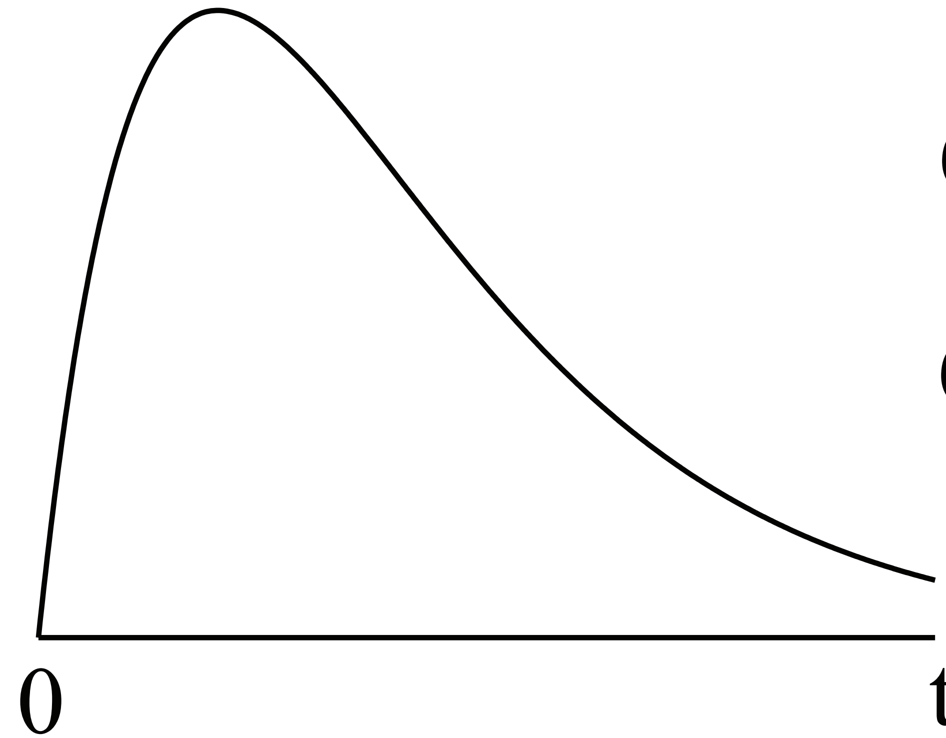
$$\dot{I} = -\frac{I}{\tau_I} + W_{II} g_{II}(A^- - I) + W_{IE} g_{IE}(A^+ - I) + P_I$$



$$\eta(t) = \alpha^2 t e^{-\alpha t}$$



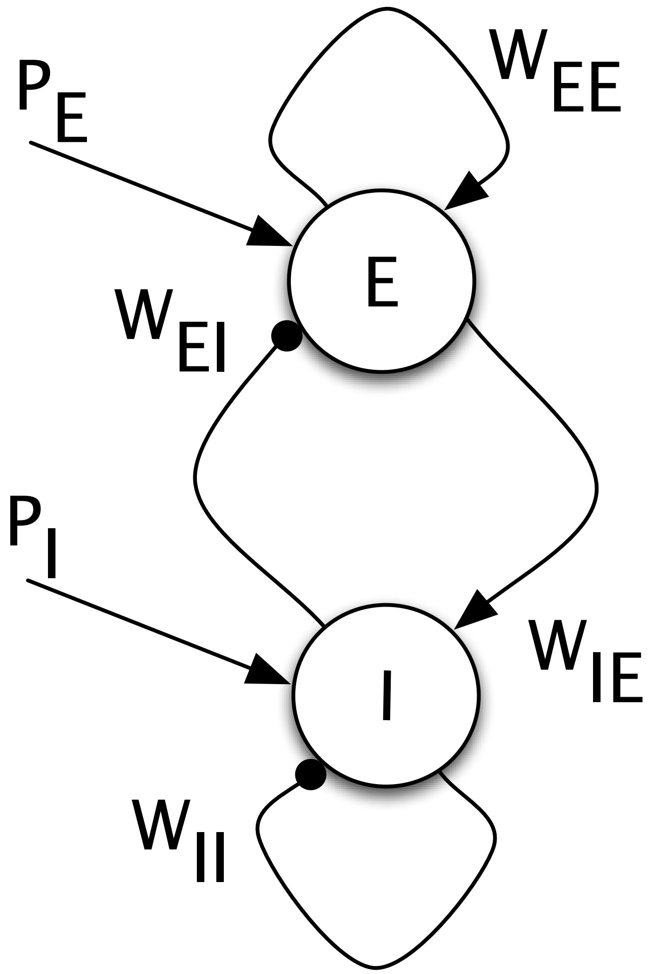


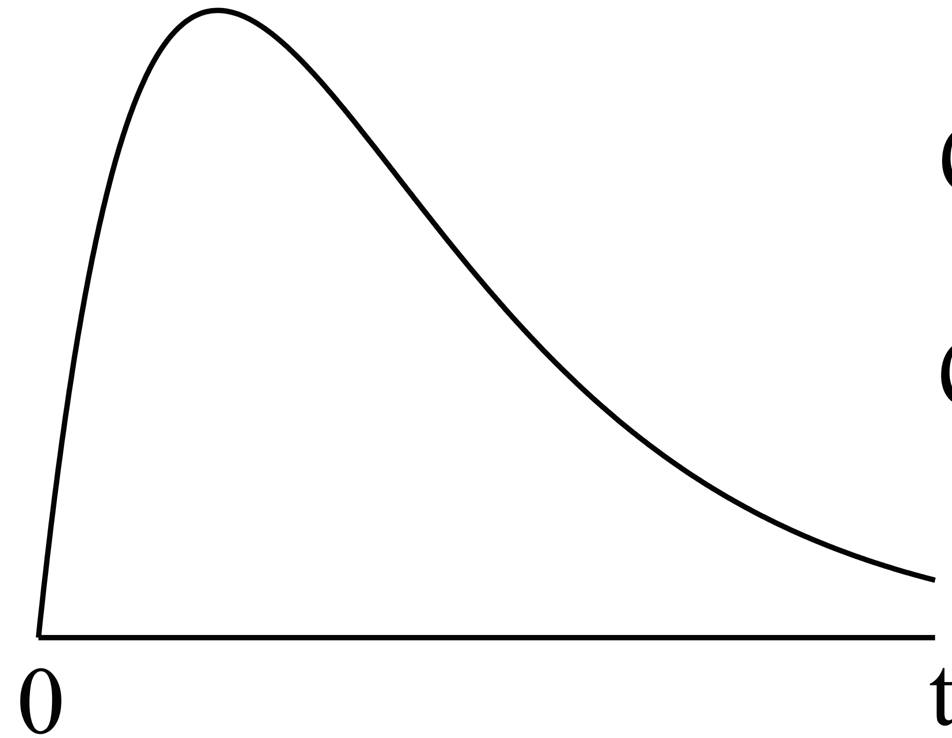


$$\eta(t) = \alpha^2 t e^{-\alpha t}$$

$$Q\eta = \delta$$

$$Q = \left(1 + \frac{1}{\alpha}\frac{d}{dt}\right)^2$$





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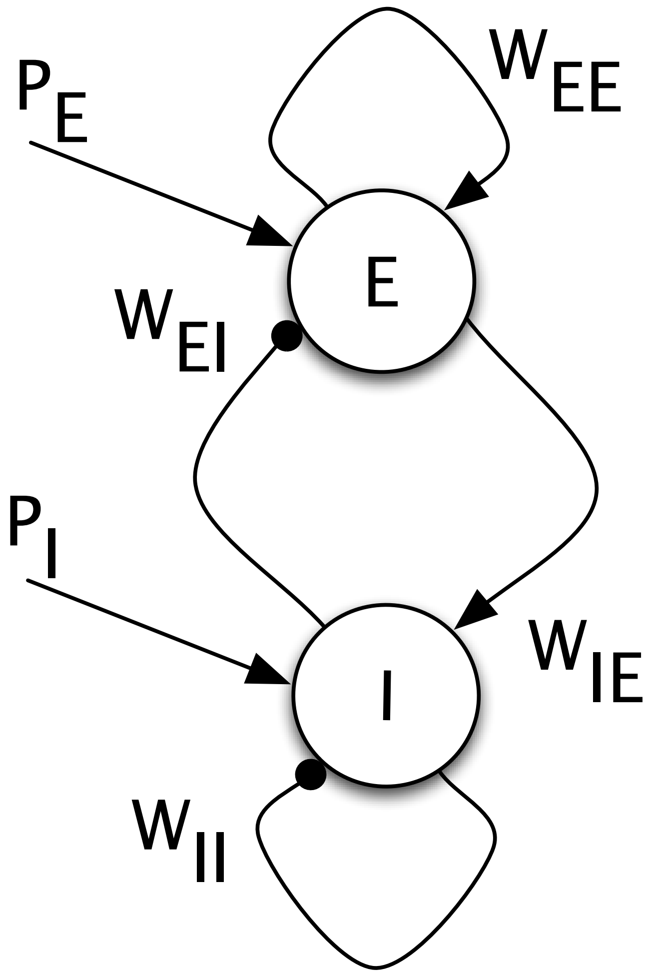

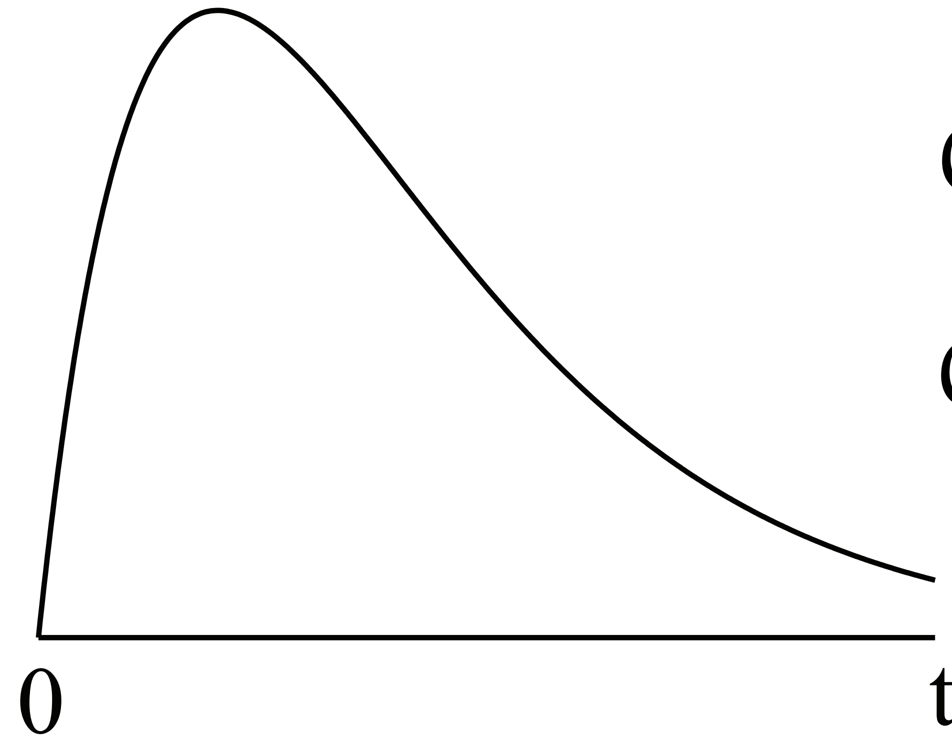

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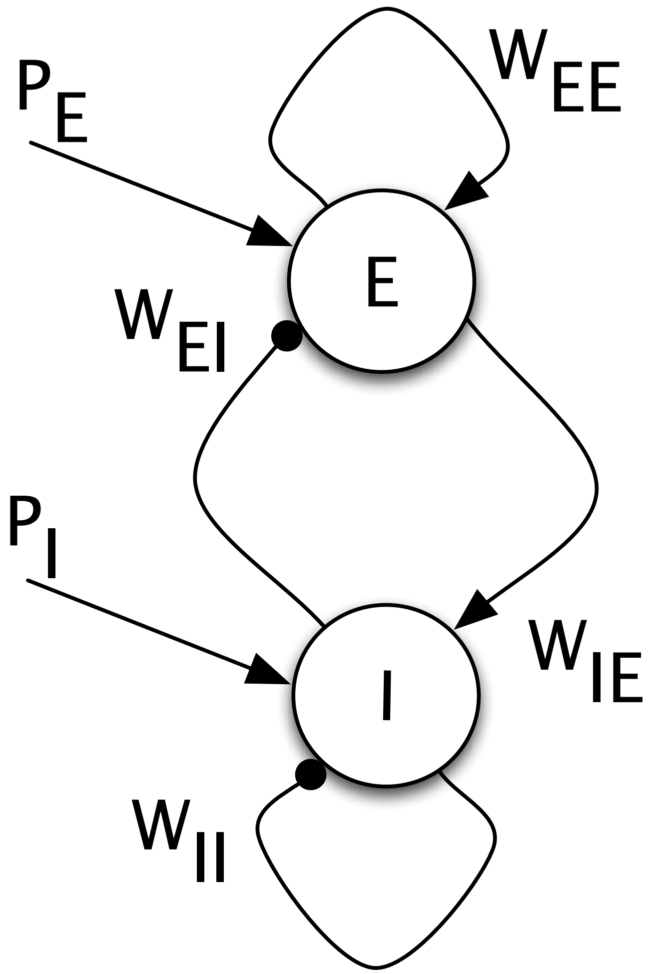
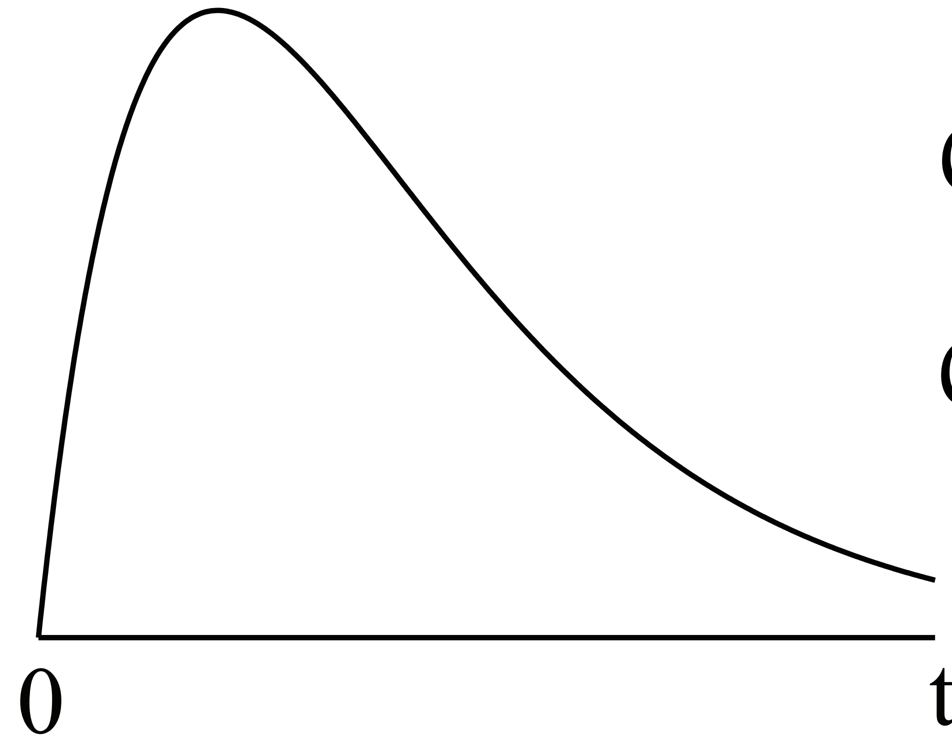
Steady state approximation

$$I = I(g_{II}, g_{IE}) \qquad E = E(g_{EE}, g_{EI})$$





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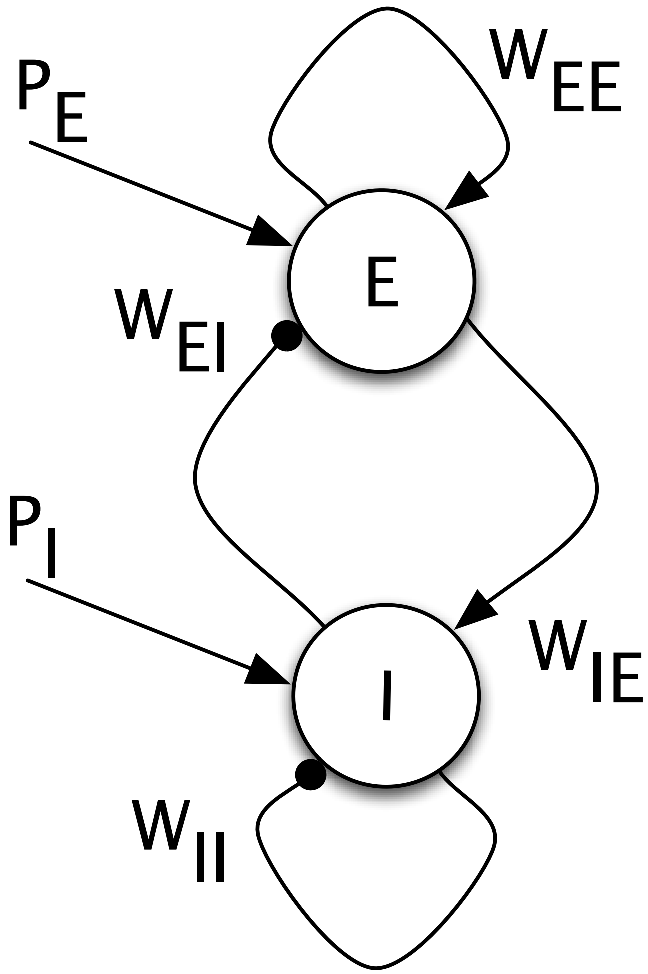

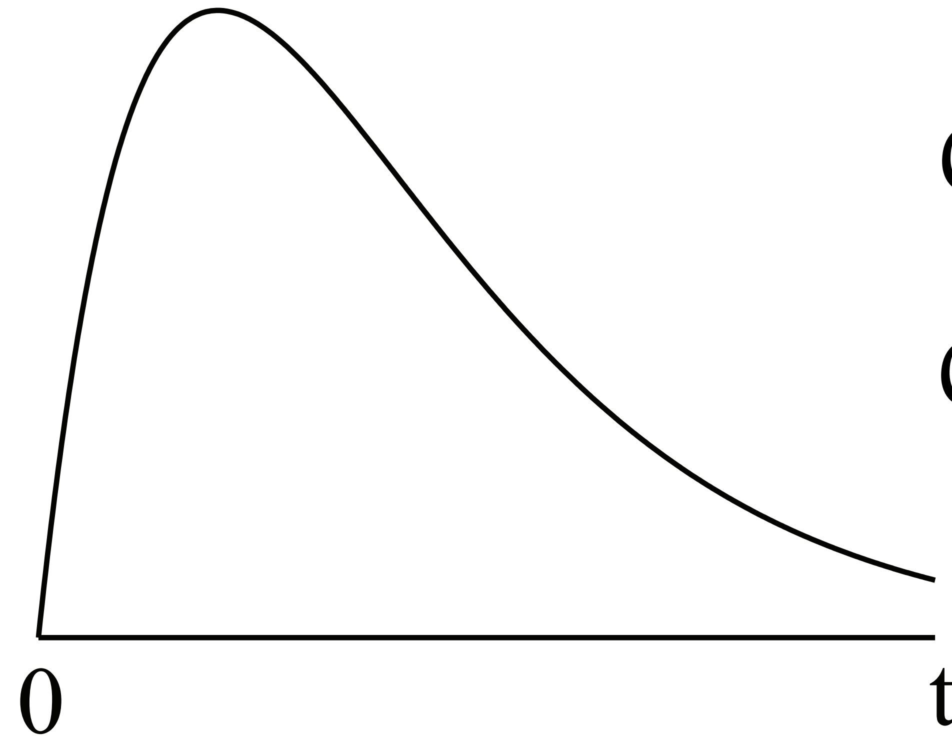

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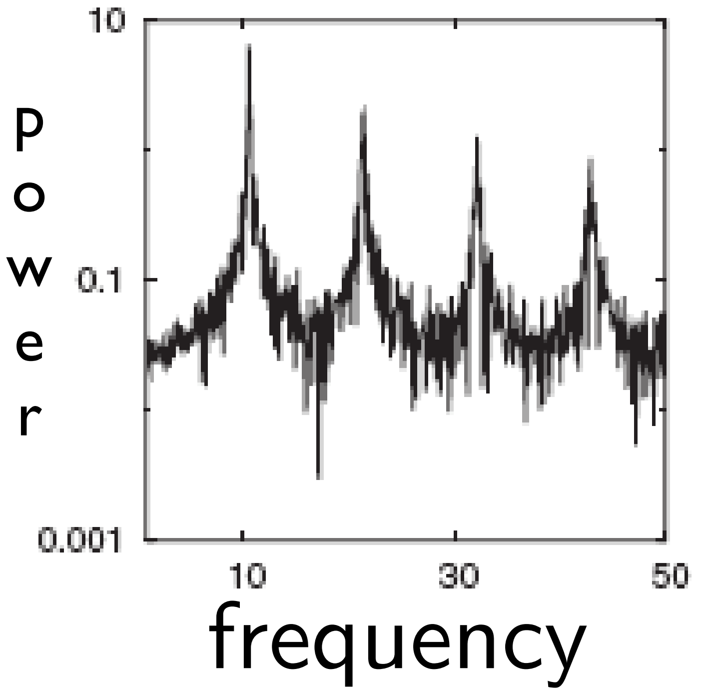
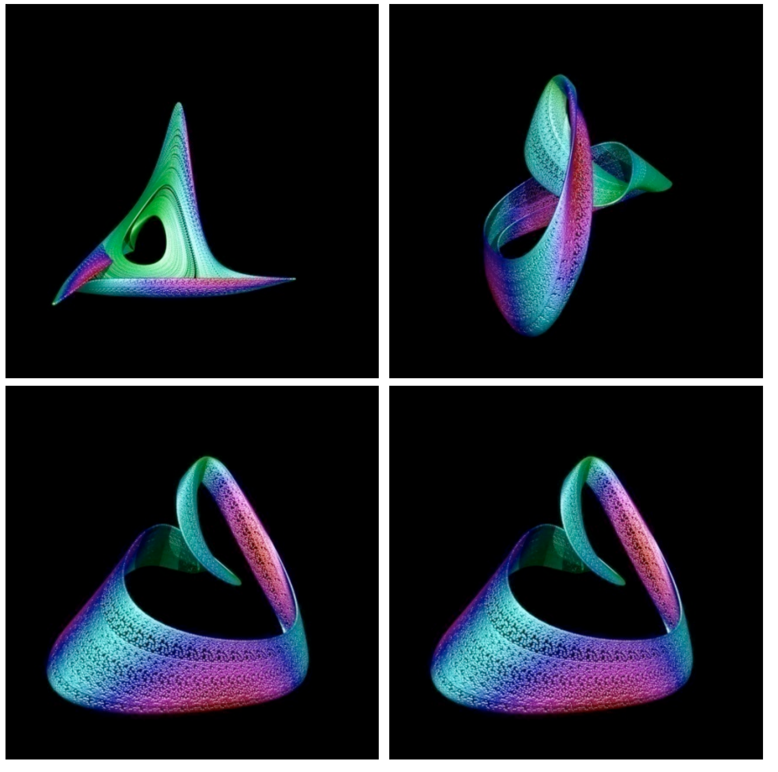
Alphoid chaos





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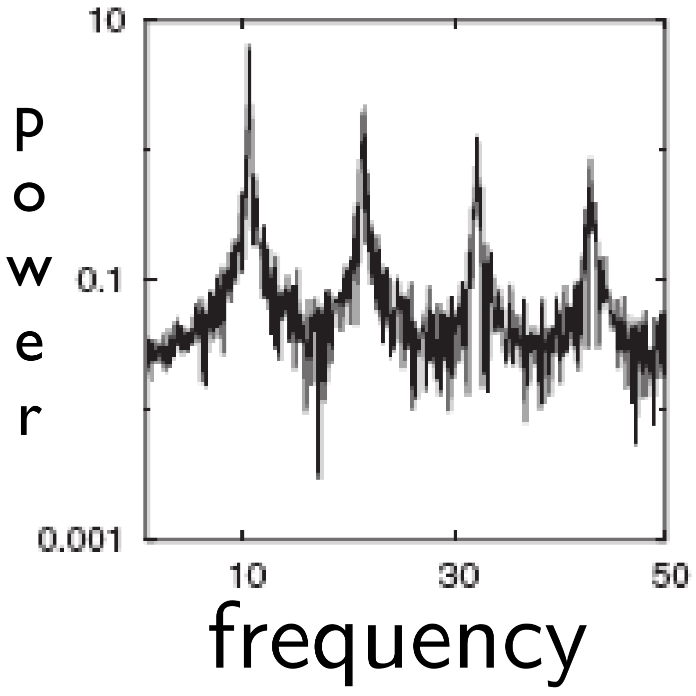

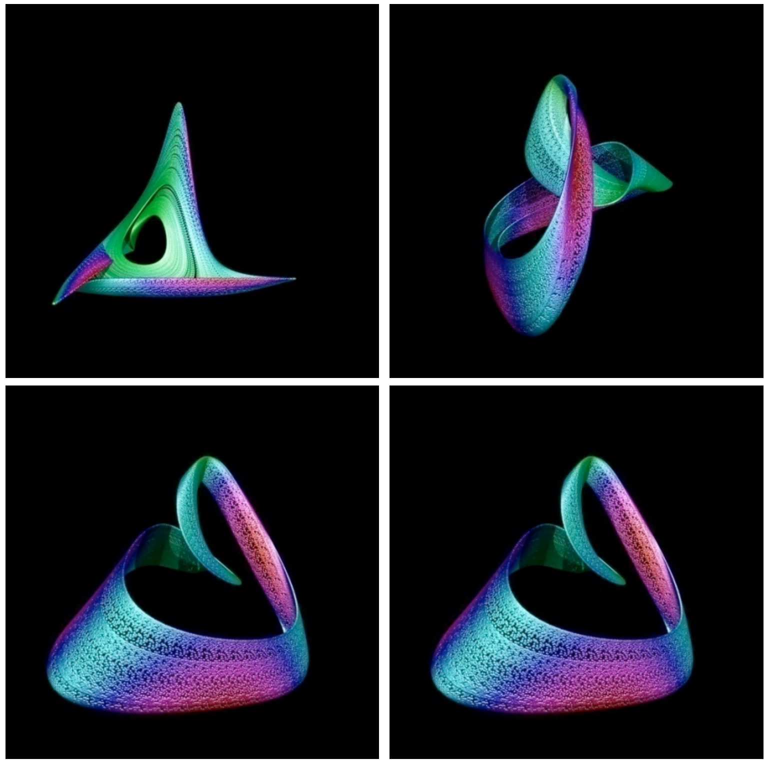

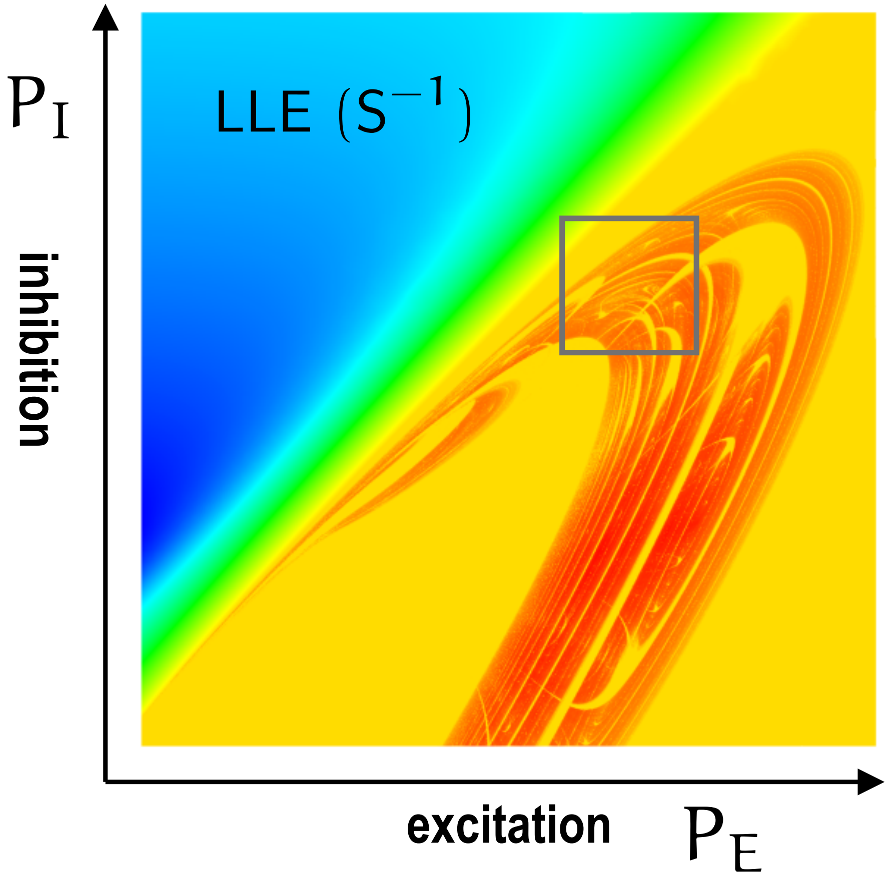

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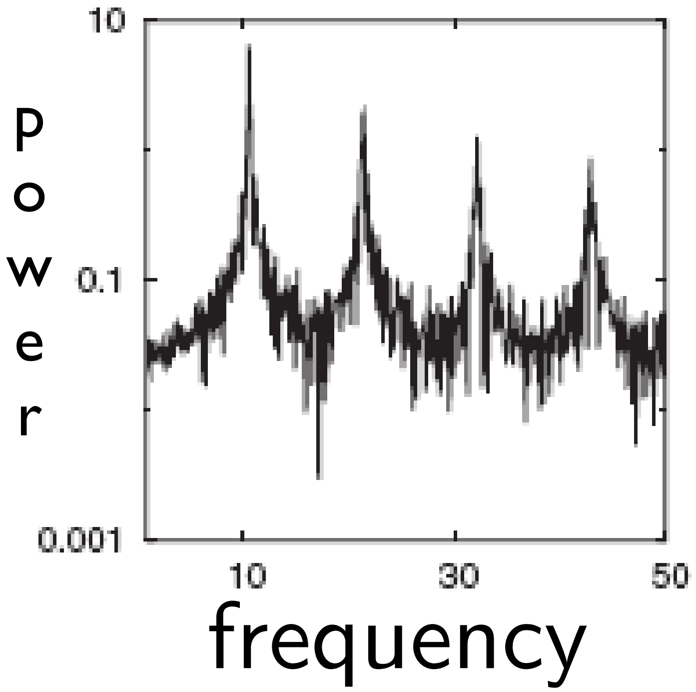

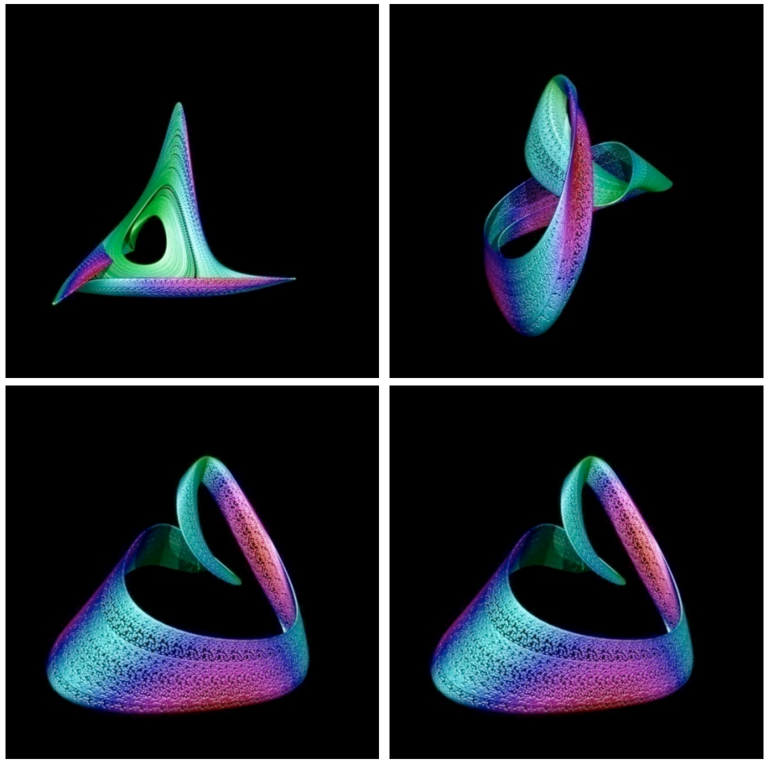

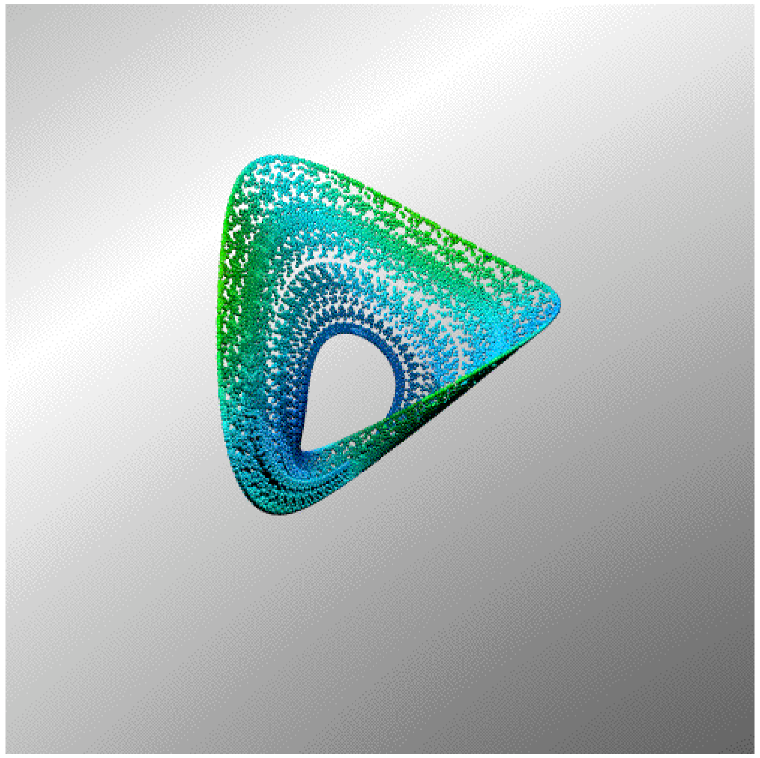

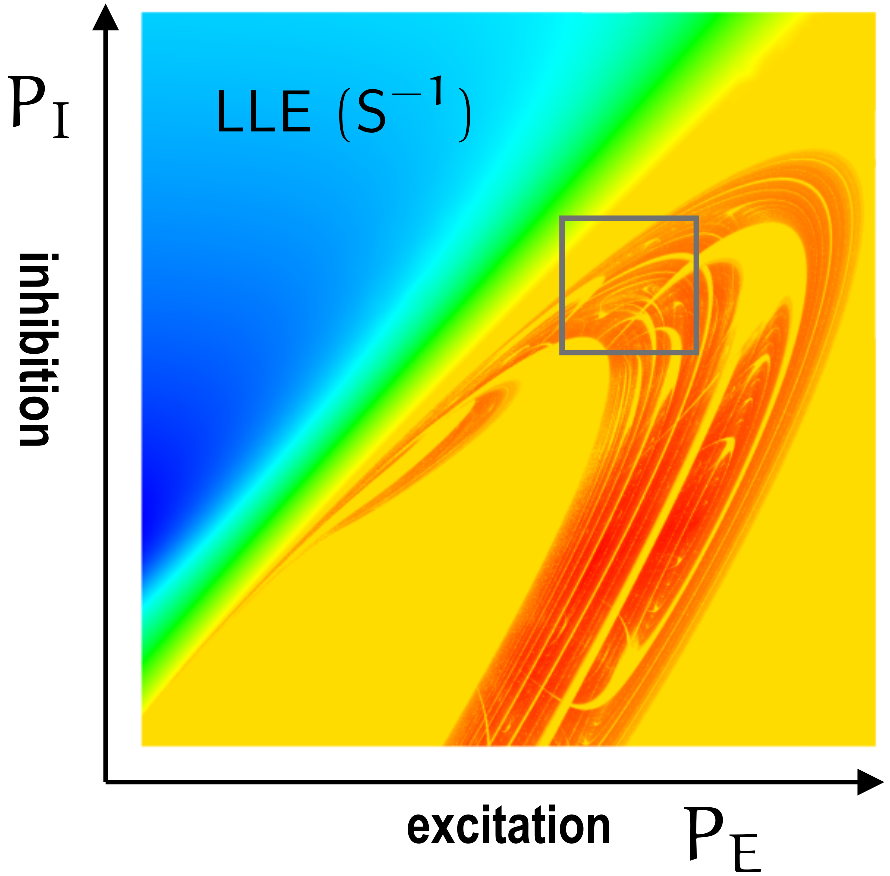

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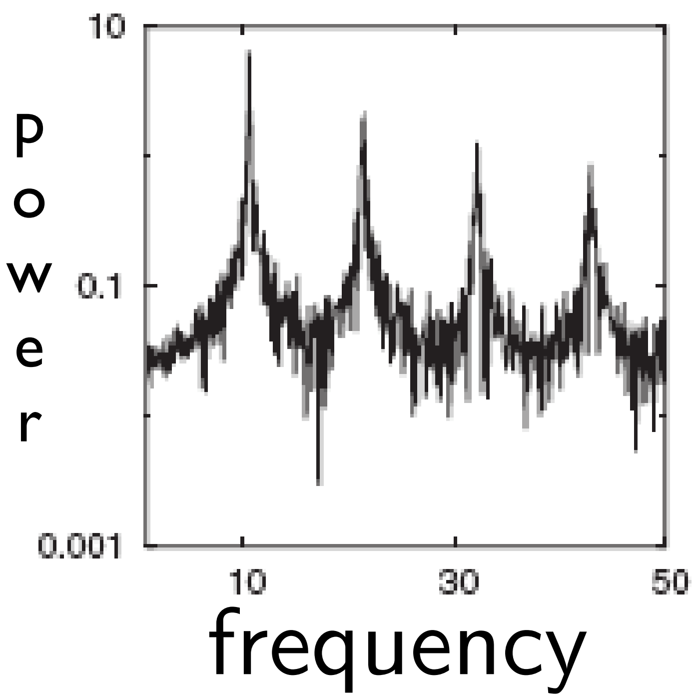

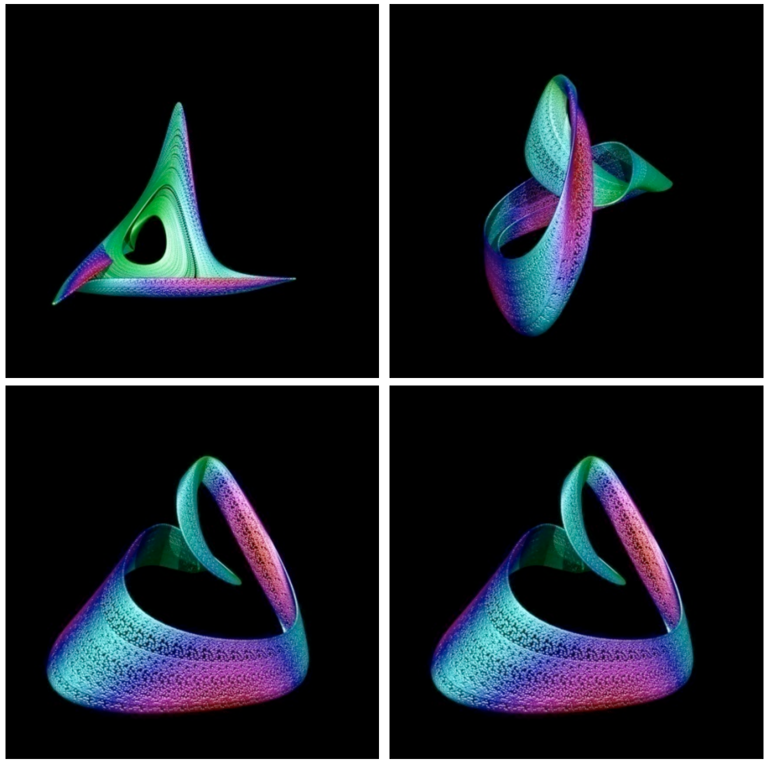

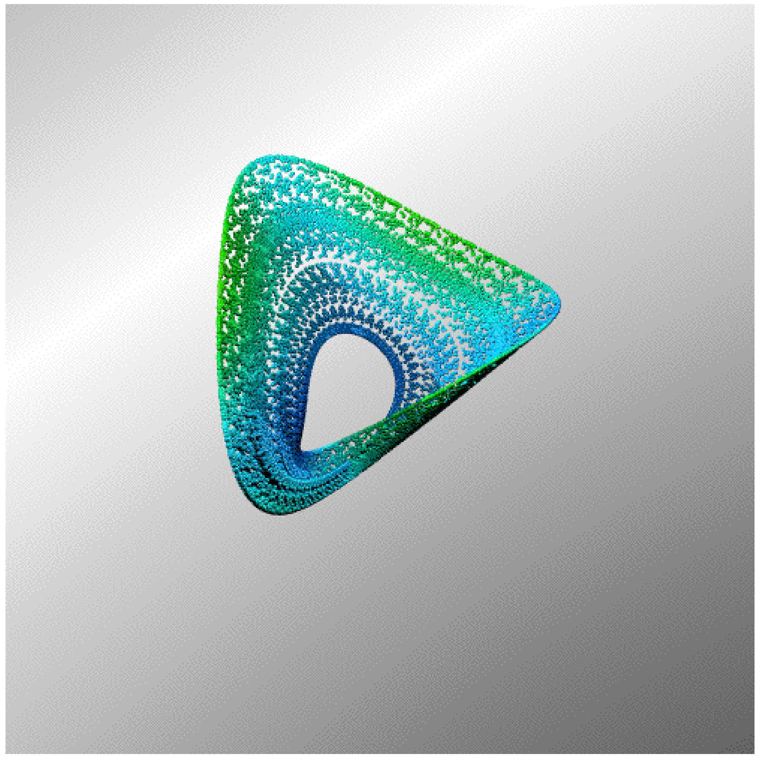

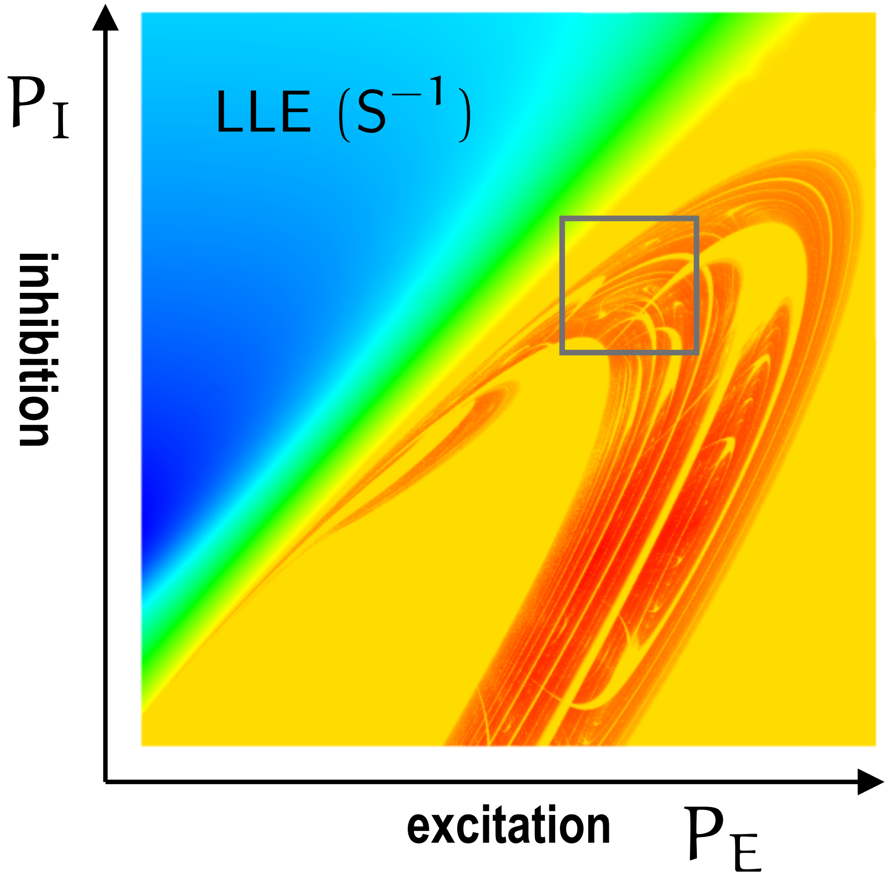

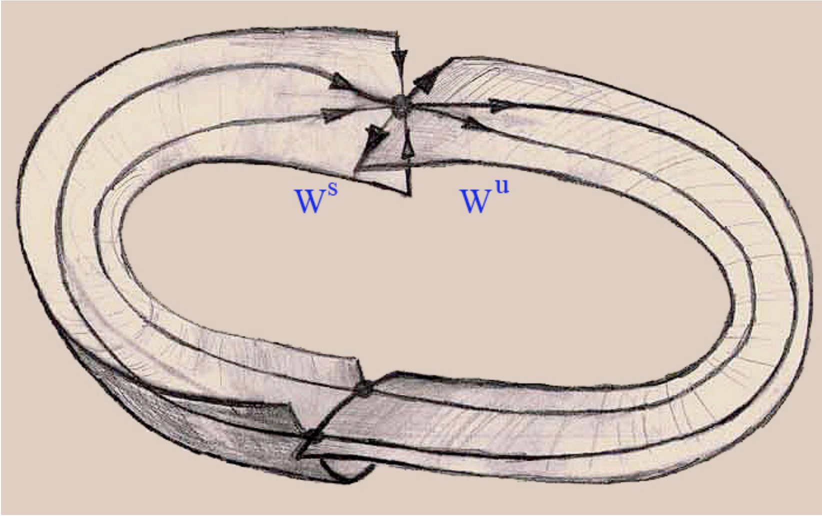

Shilnikov saddle-node route to chaos

van Veen and Liley, PRL, **97**, 208101 (2006)

Spatially extended models

$$g = w \otimes \eta * f$$

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Simplest neural field model: Wilson-Cowan ('72), Amari ('77)

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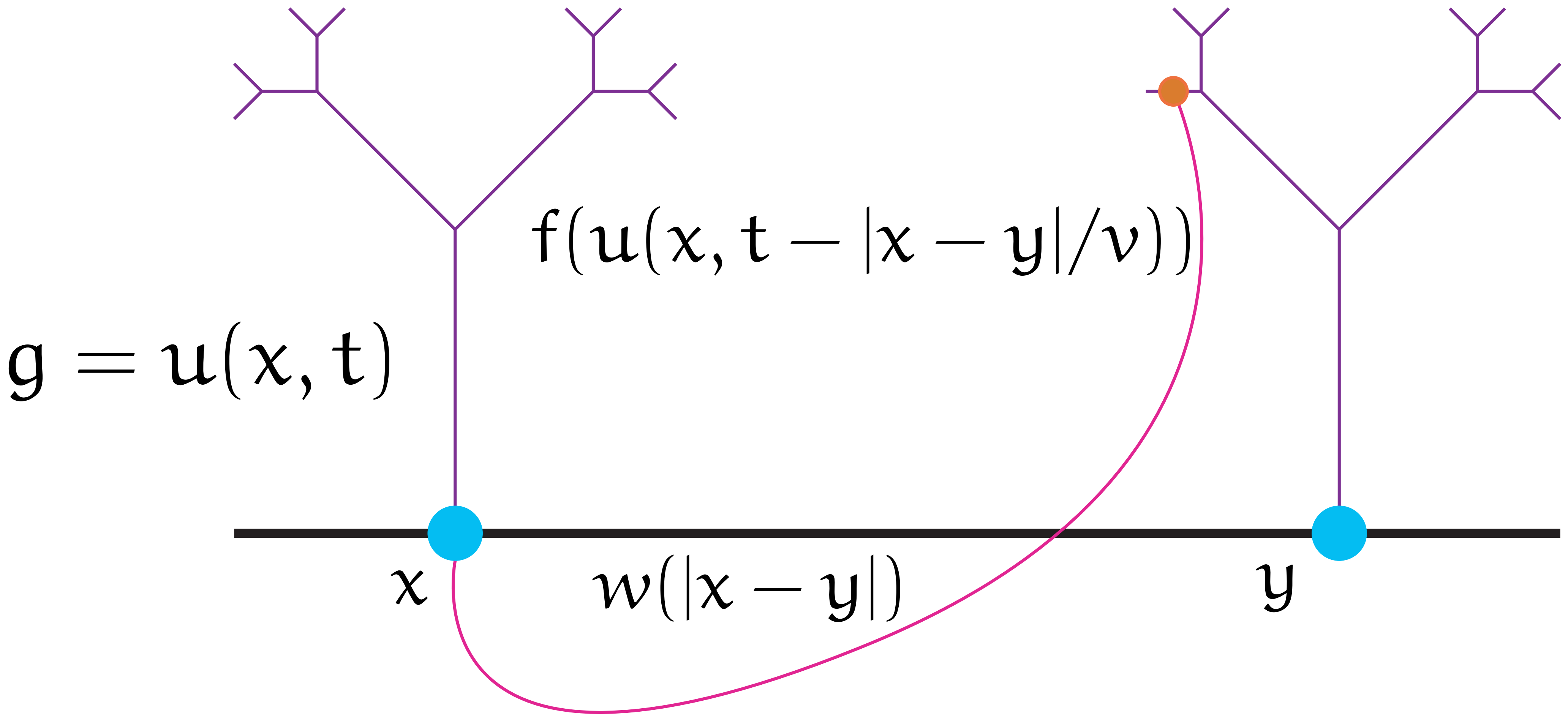

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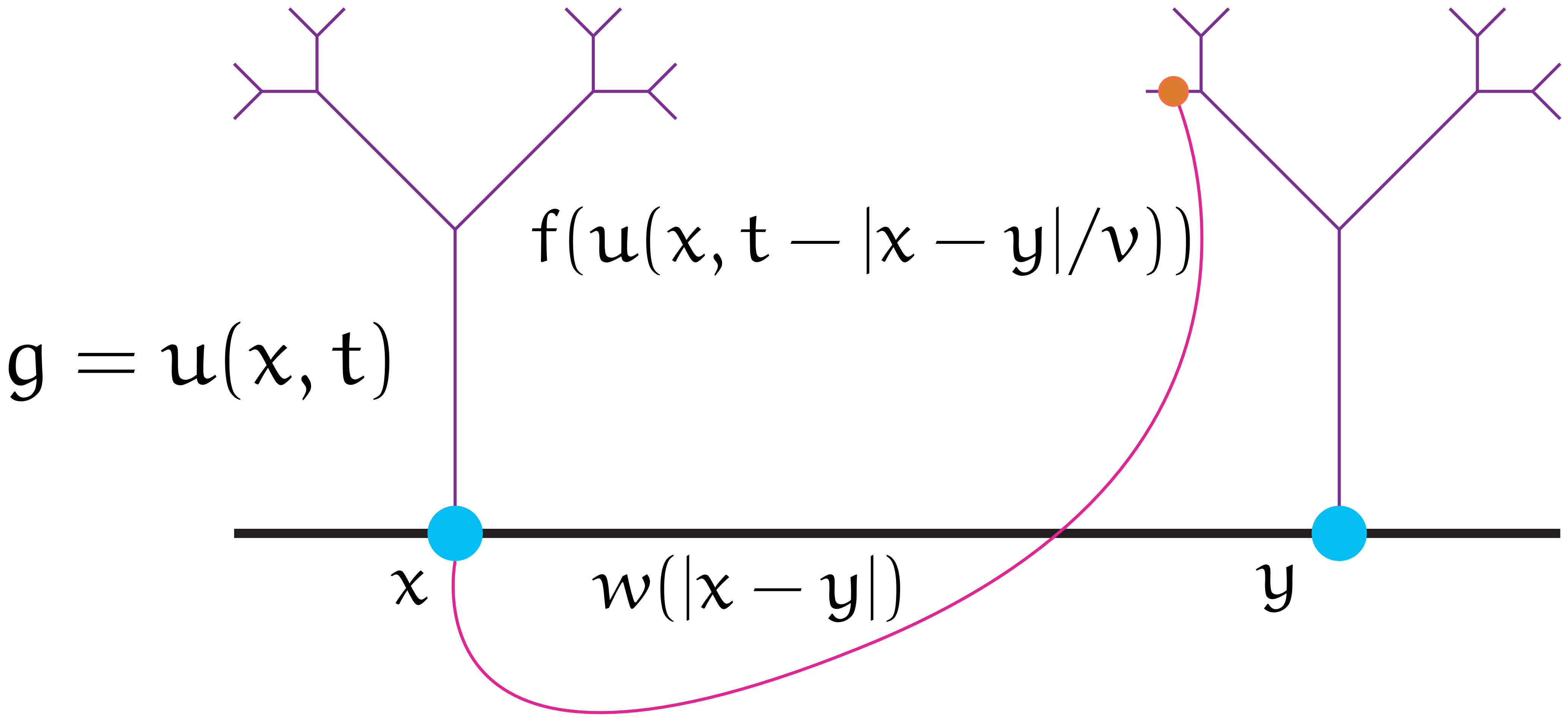
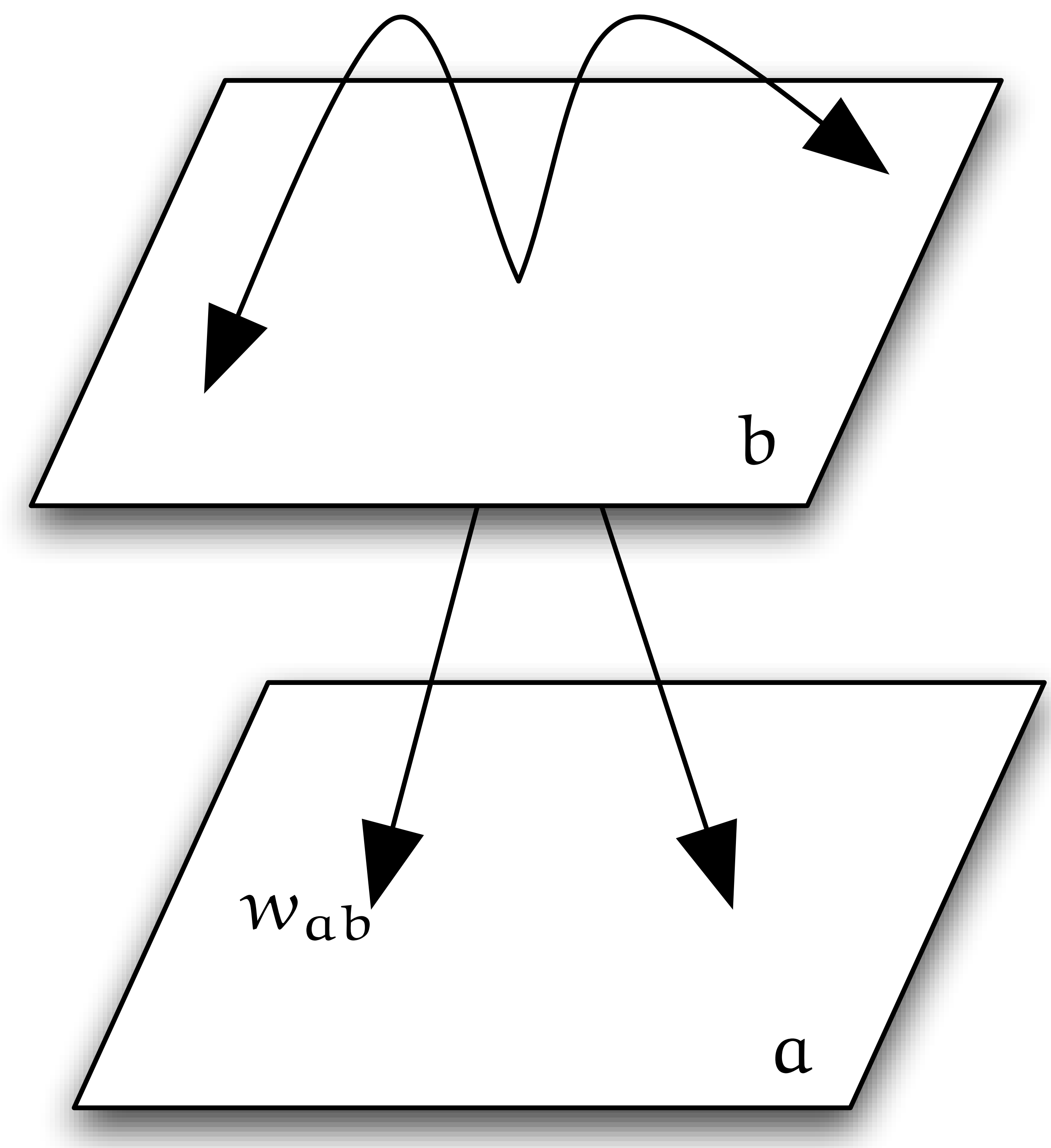


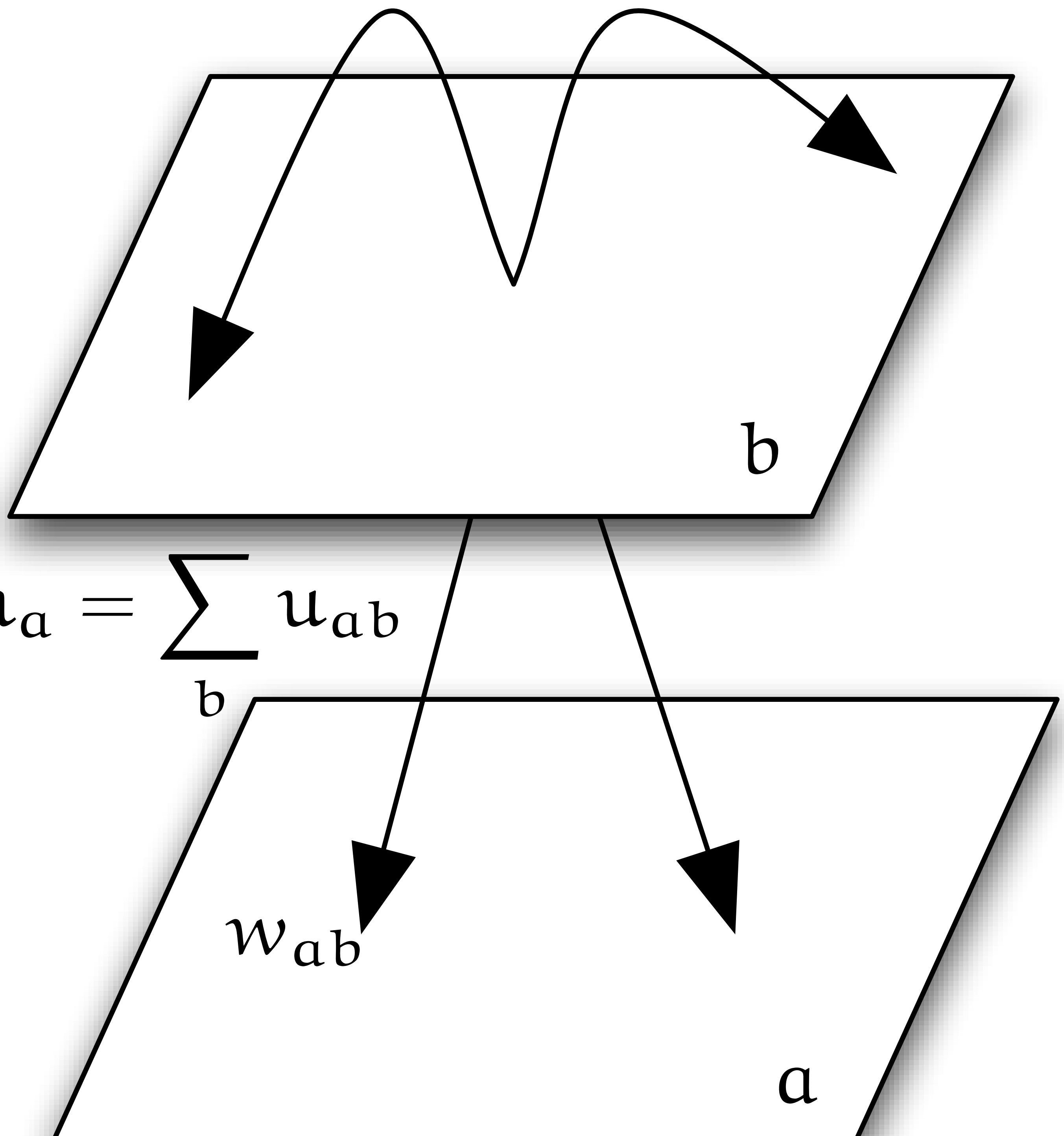
$$u(x,t) = \int_{-\infty}^{\infty} dy\ w(y) \int_0^{\infty} ds\ \eta(s)\ f\left(u(x-y, t-s-|y|/v)\right)$$

2D layers



2D layers

$$u_{ab} = \eta_{ab} * \psi_{ab}$$



$$h_a = \sum_b u_{ab}$$

$$\psi_{ab}(\mathbf{r}, t) = \int_{\mathbb{R}^2} d\mathbf{r}' \, w_{ab}(\mathbf{r}, \mathbf{r}') f_b \circ h_b \left(\mathbf{r}', t - |\mathbf{r} - \mathbf{r}'|/v_{ab}\right)$$

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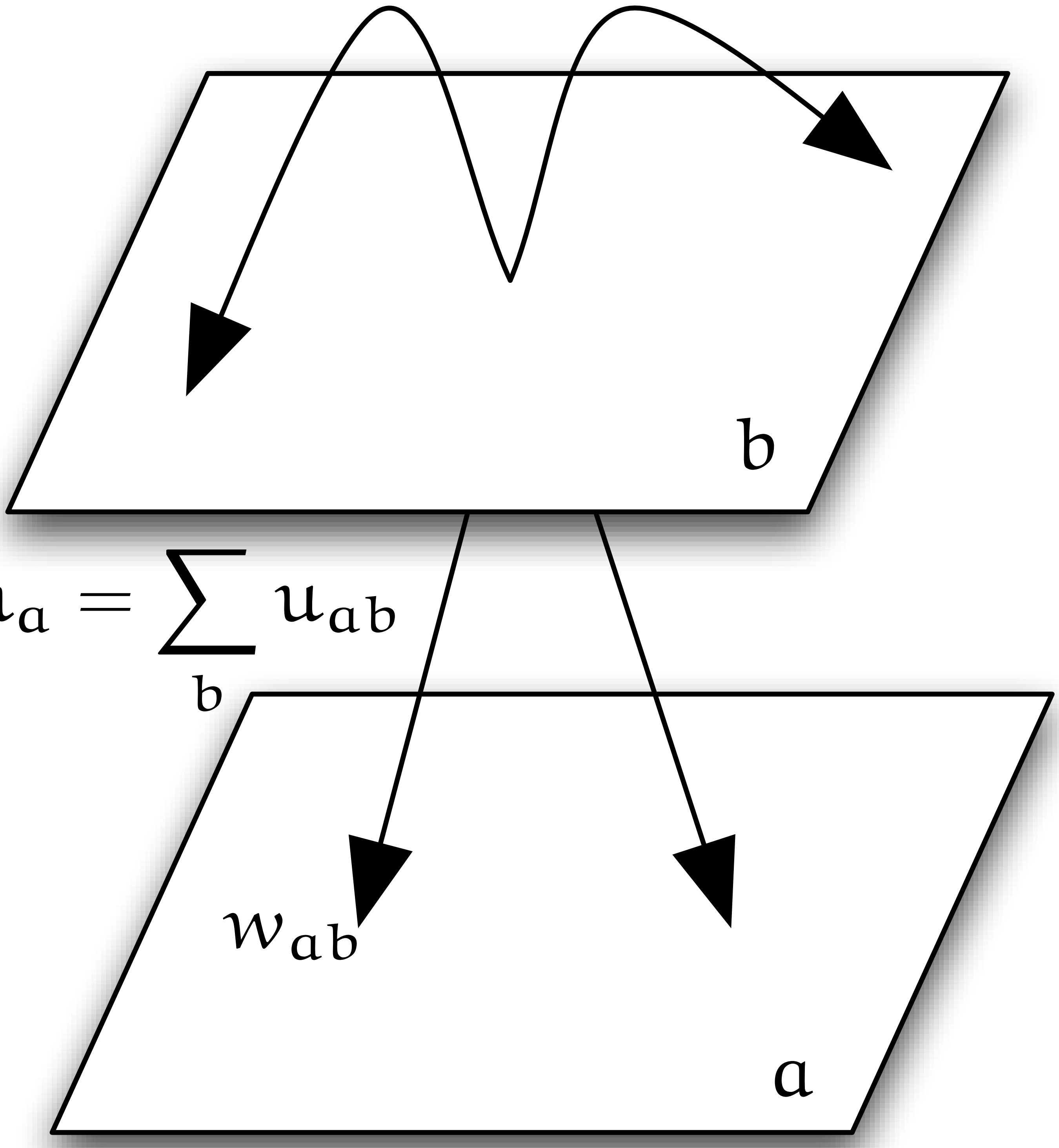

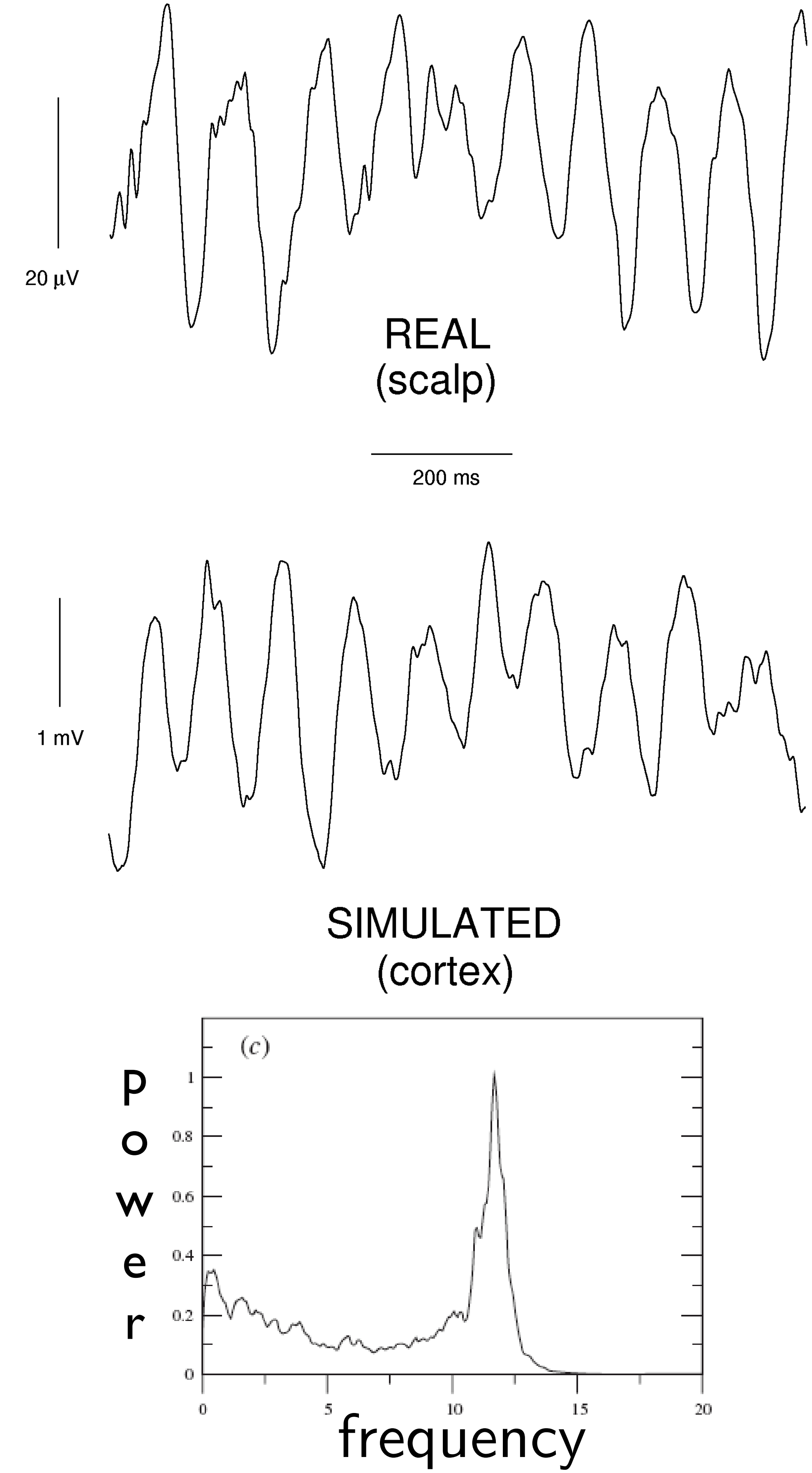

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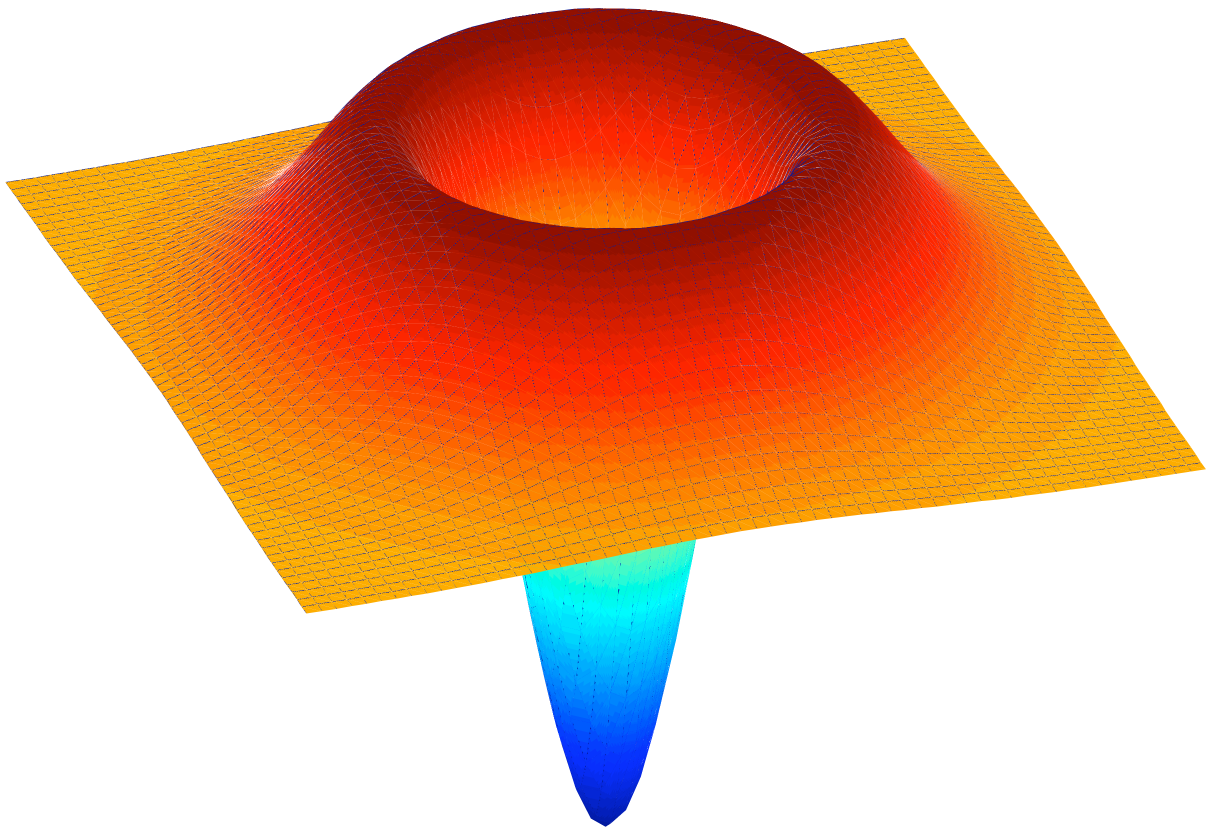
Turing instability analysis

E layer and I layer



Turing instability analysis

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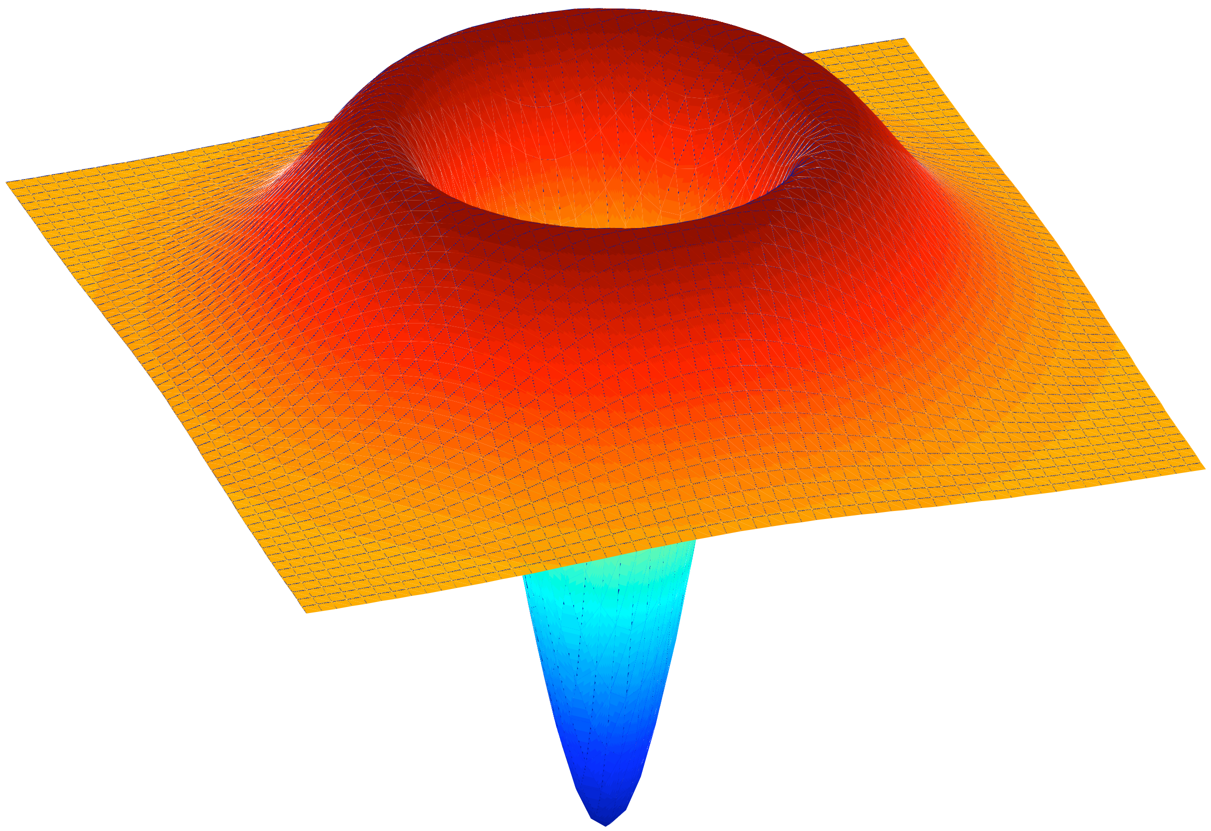
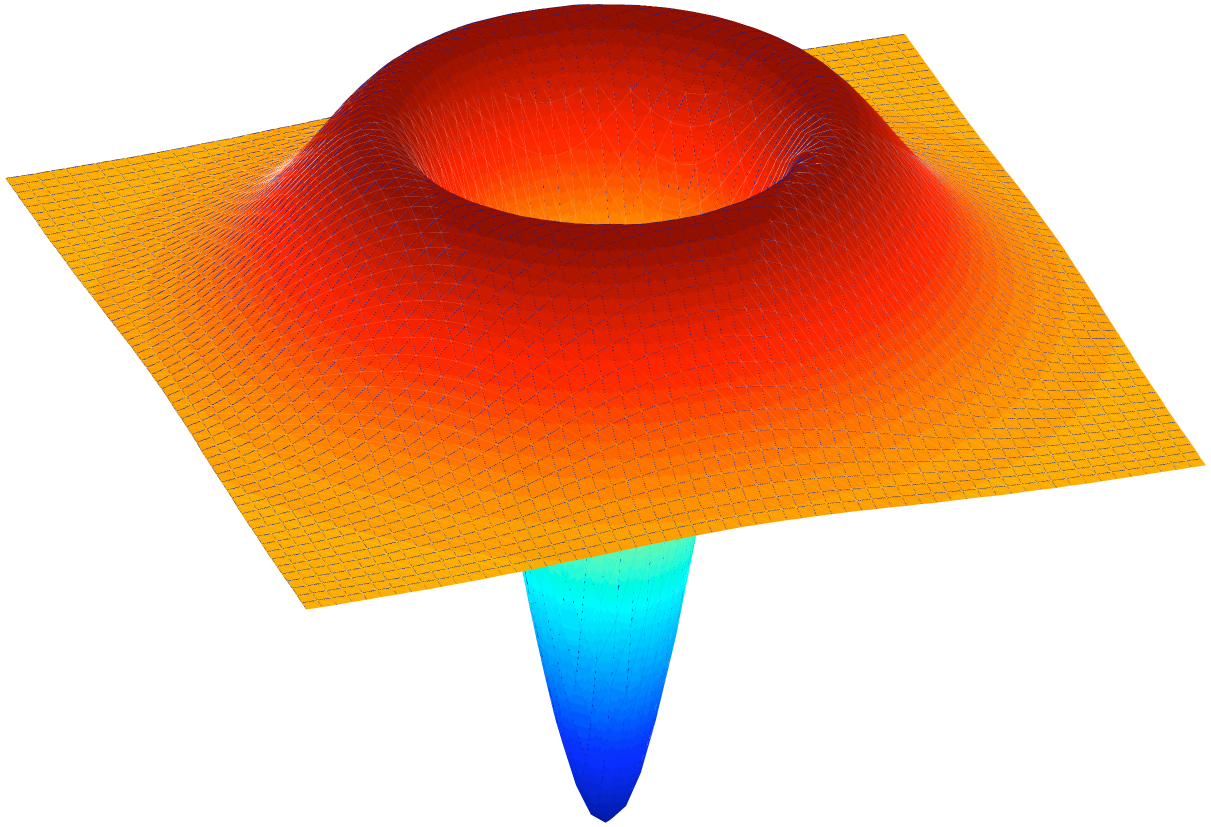


$$e^{i\mathbf{k}\cdot\mathbf{r}} e^{\lambda t}$$

Turing instability analysis

E layer and I layer



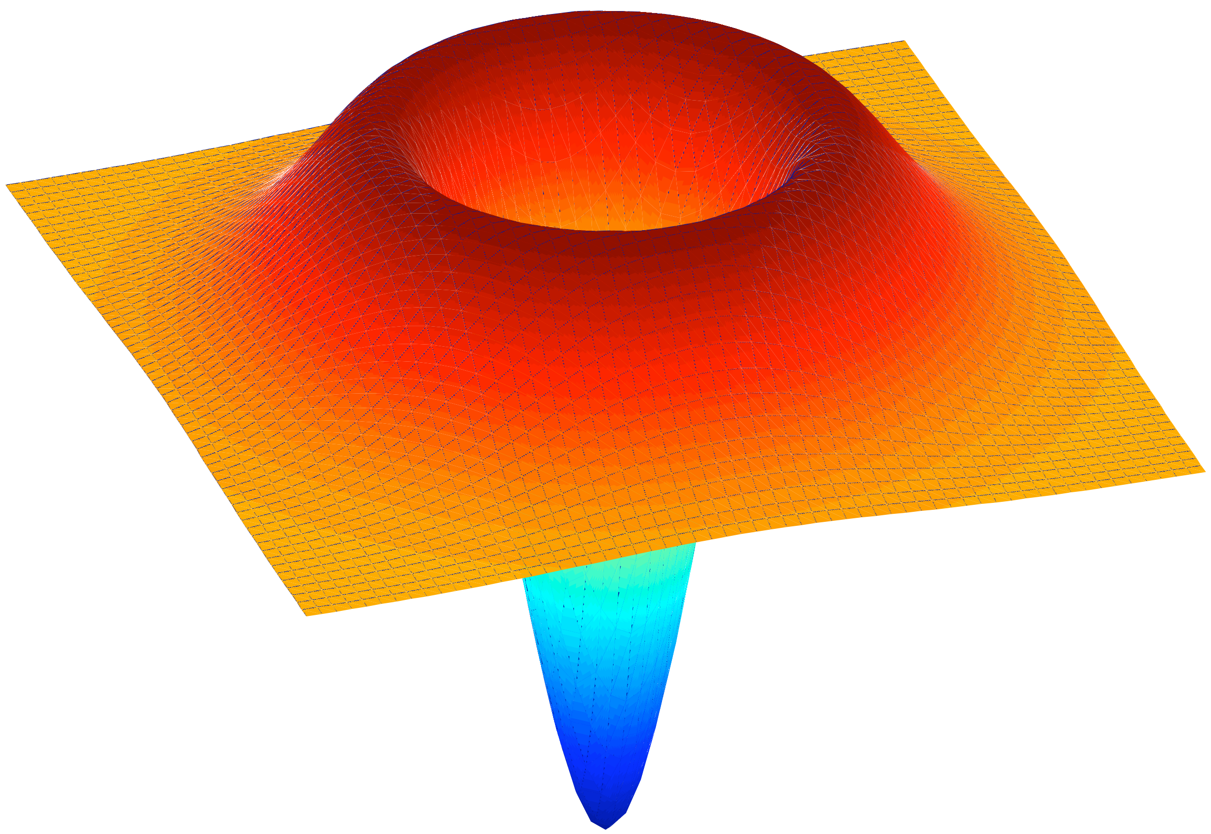
$$e^{i\mathbf{k}\cdot\mathbf{r}}e^{\lambda t}$$

Continuous spectrum

$$\det\left(\mathcal{D}(k,\lambda) - I\right) = 0$$

Turing instability analysis

E layer and I layer



$$e^{i\mathbf{k}\cdot\mathbf{r}}e^{\lambda t}$$

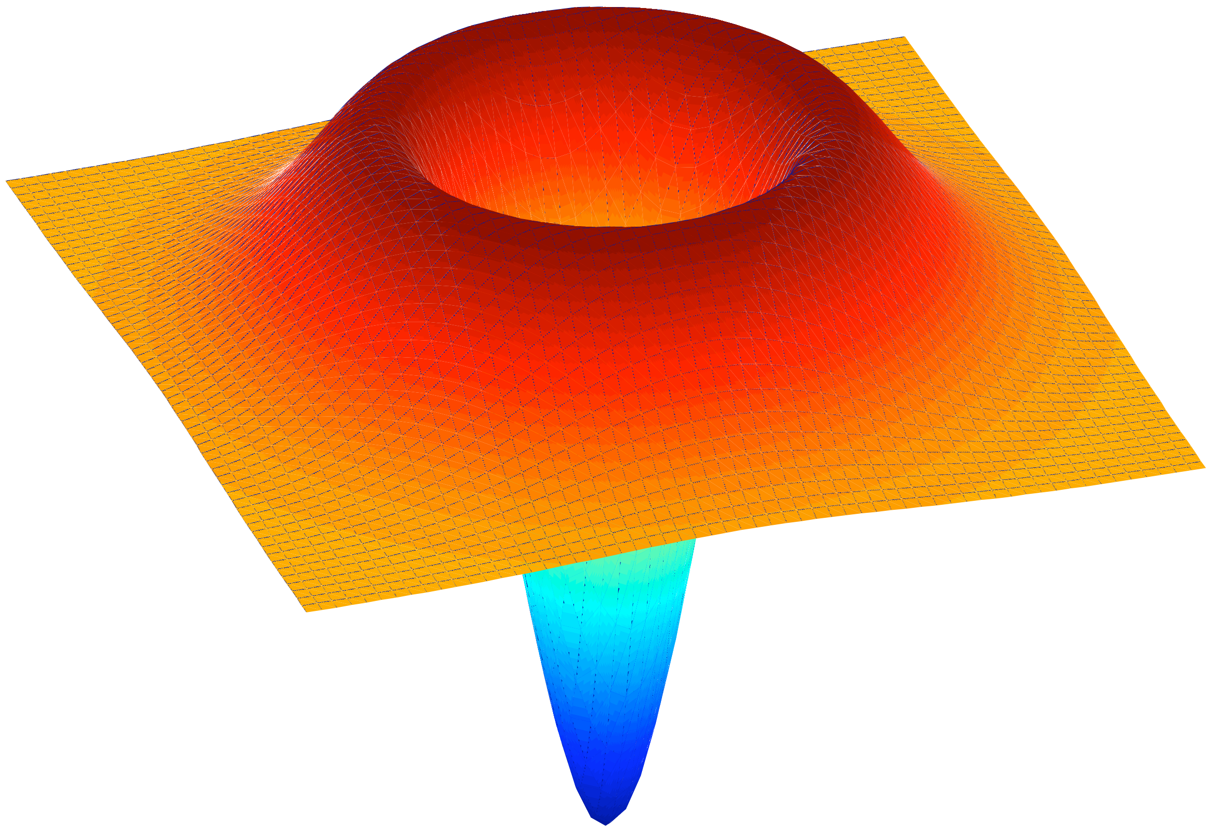
Continuous spectrum

$$\det\left(\mathcal{D}(k,\lambda) - I\right) = 0$$

$$[\mathcal{D}(k,\lambda)]_{ab} = \widetilde{\eta}_{ab}(\lambda) G_{ab}(k, -i\lambda)\gamma_b$$

Turing instability analysis

E layer and I layer



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$$\widetilde{\eta} = \text{LT}\ \eta$$

Turing instability analysis

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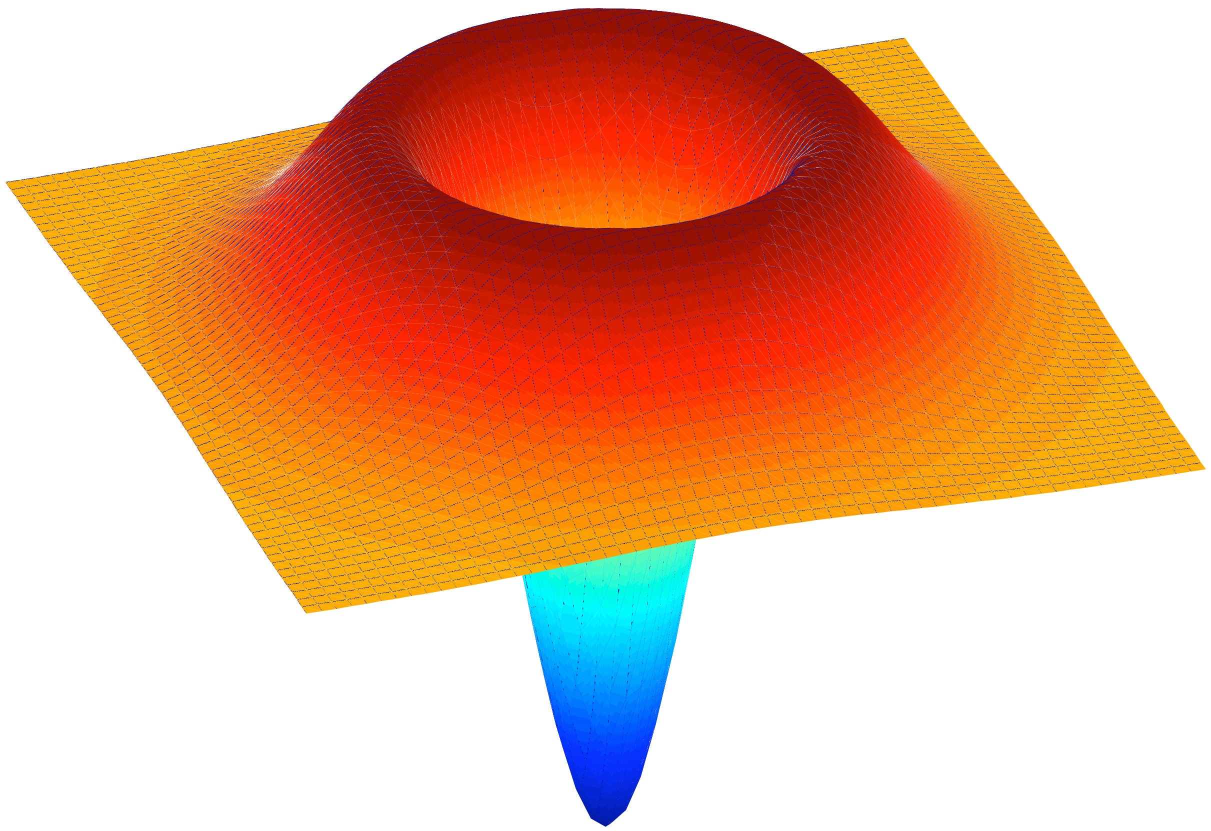

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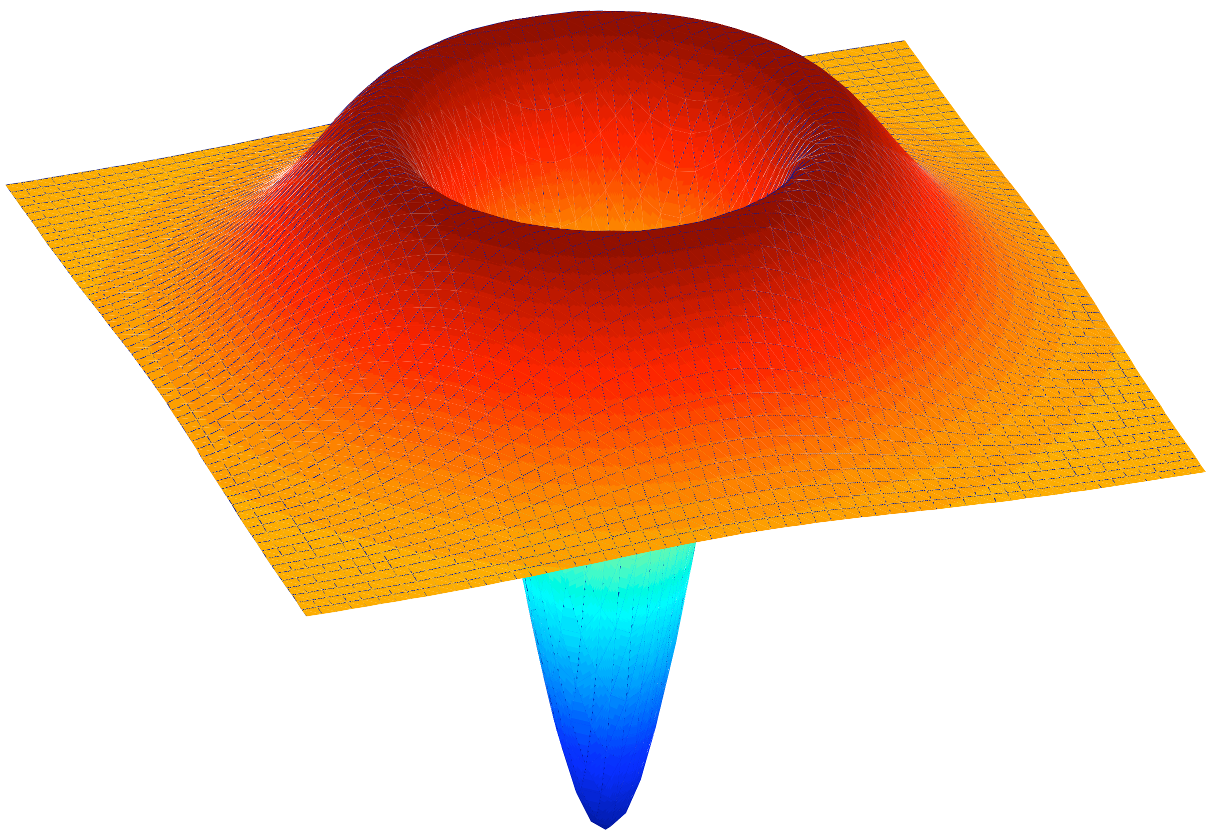
Turing instability analysis

E layer and I layer



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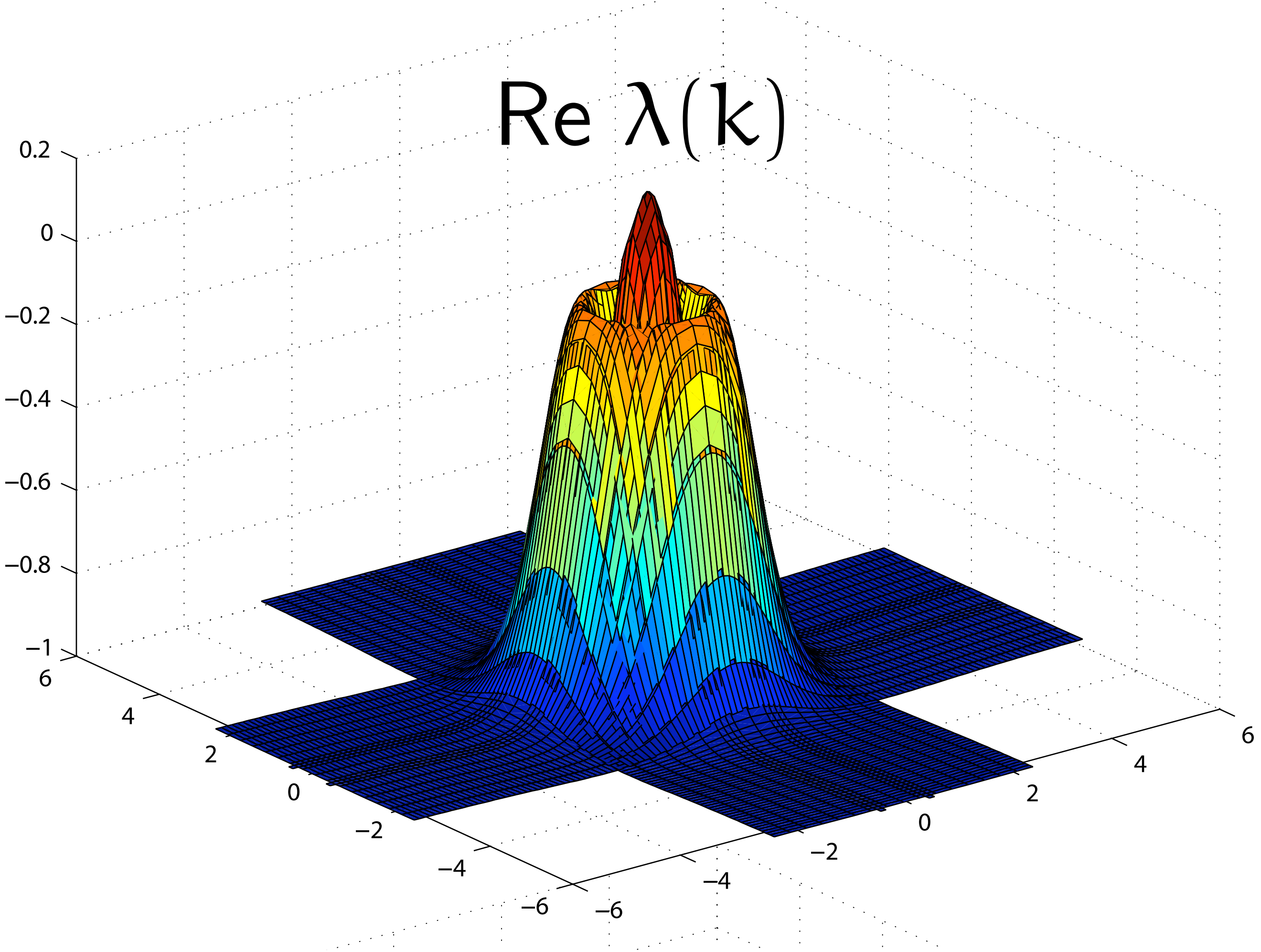
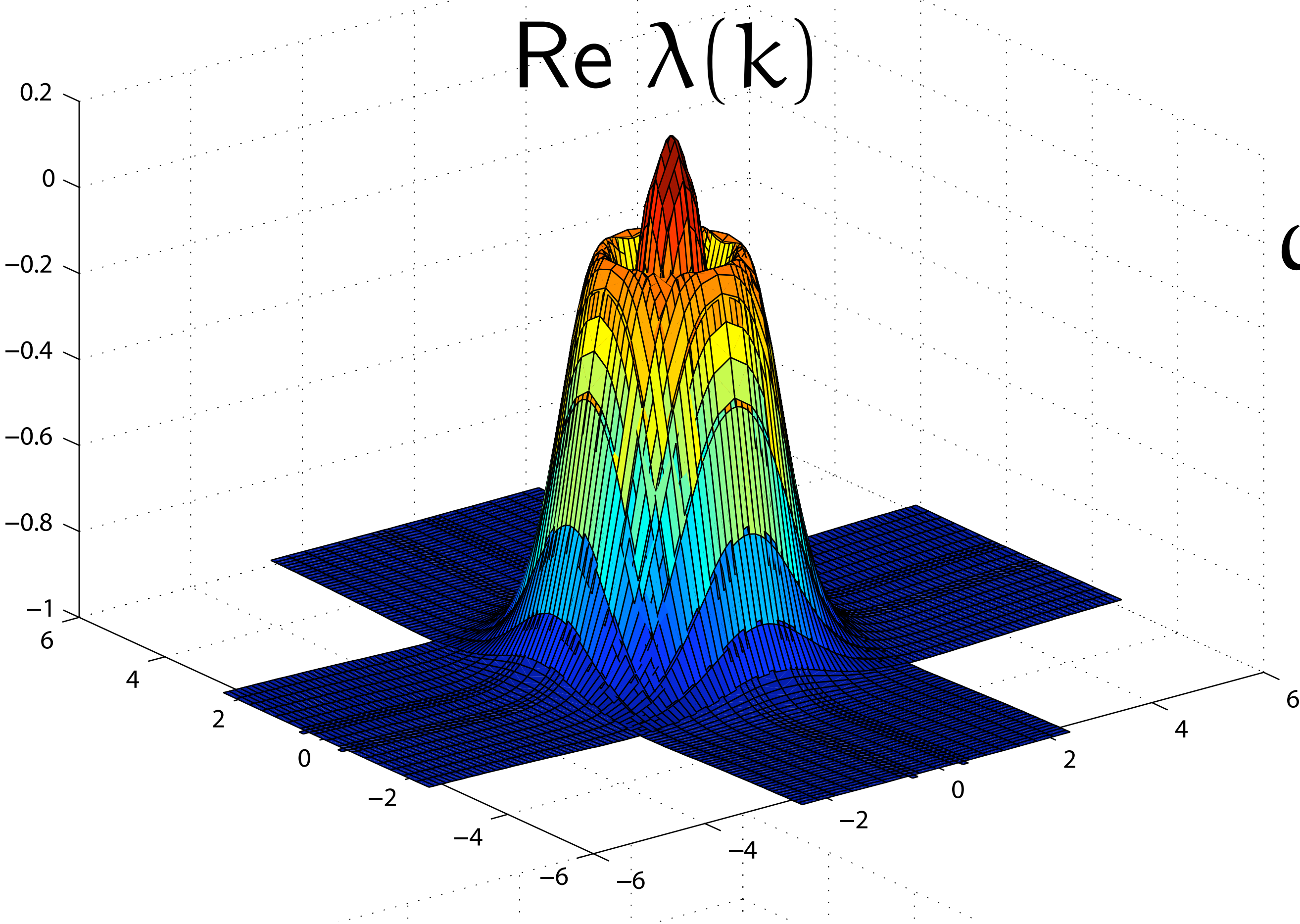
$\widetilde{\eta} = \text{LT } \eta$ $\quad$ $G = \text{FLT } w(r)\delta(t - r/v)$ $\quad$ $\gamma = f'(ss)$

S Coombes et al., PRE, **76**, 05190 (2007)



Re λ(k)
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
6
4
2
0
−2
−4
−6
−6
−4
−2
0
2
4
6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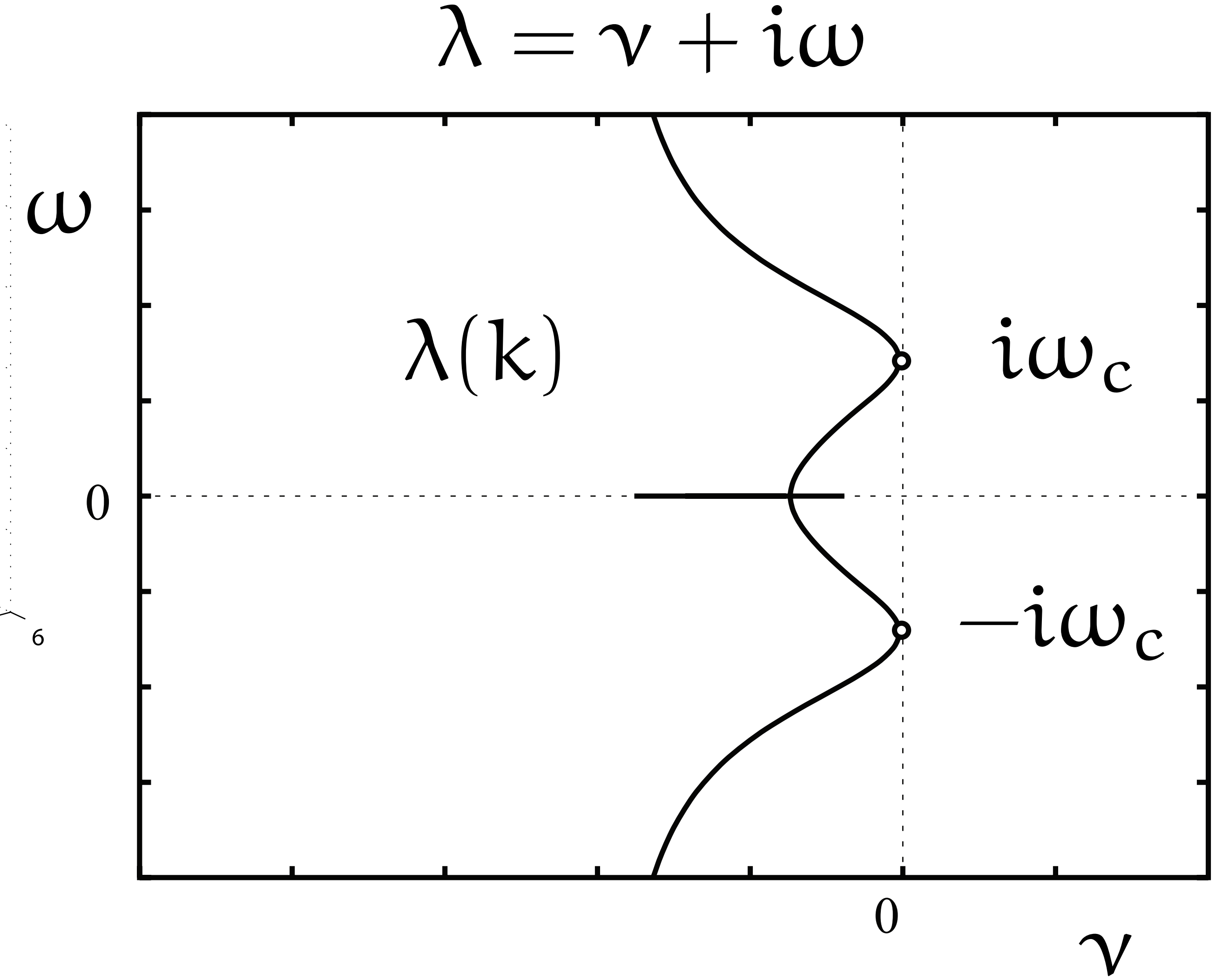
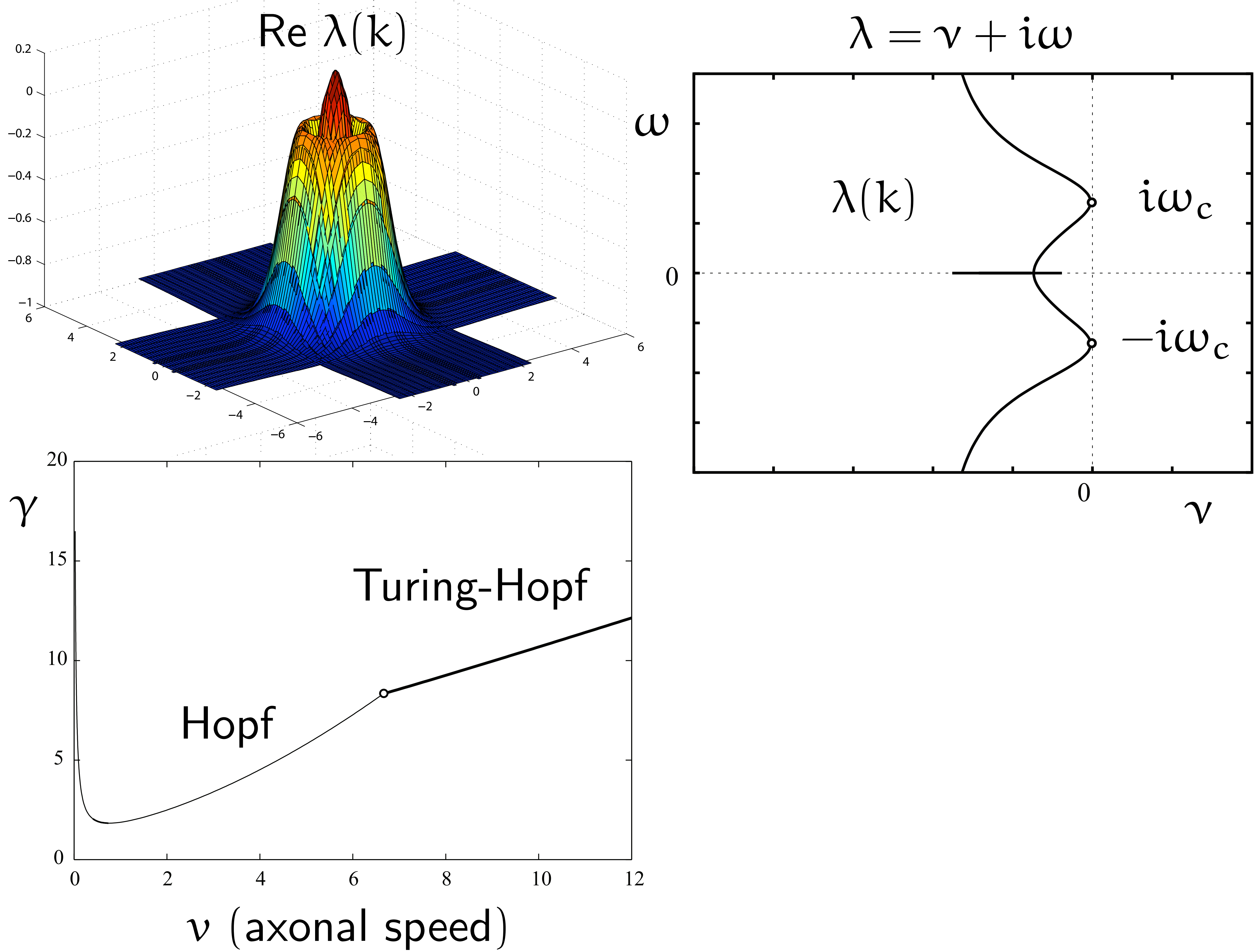
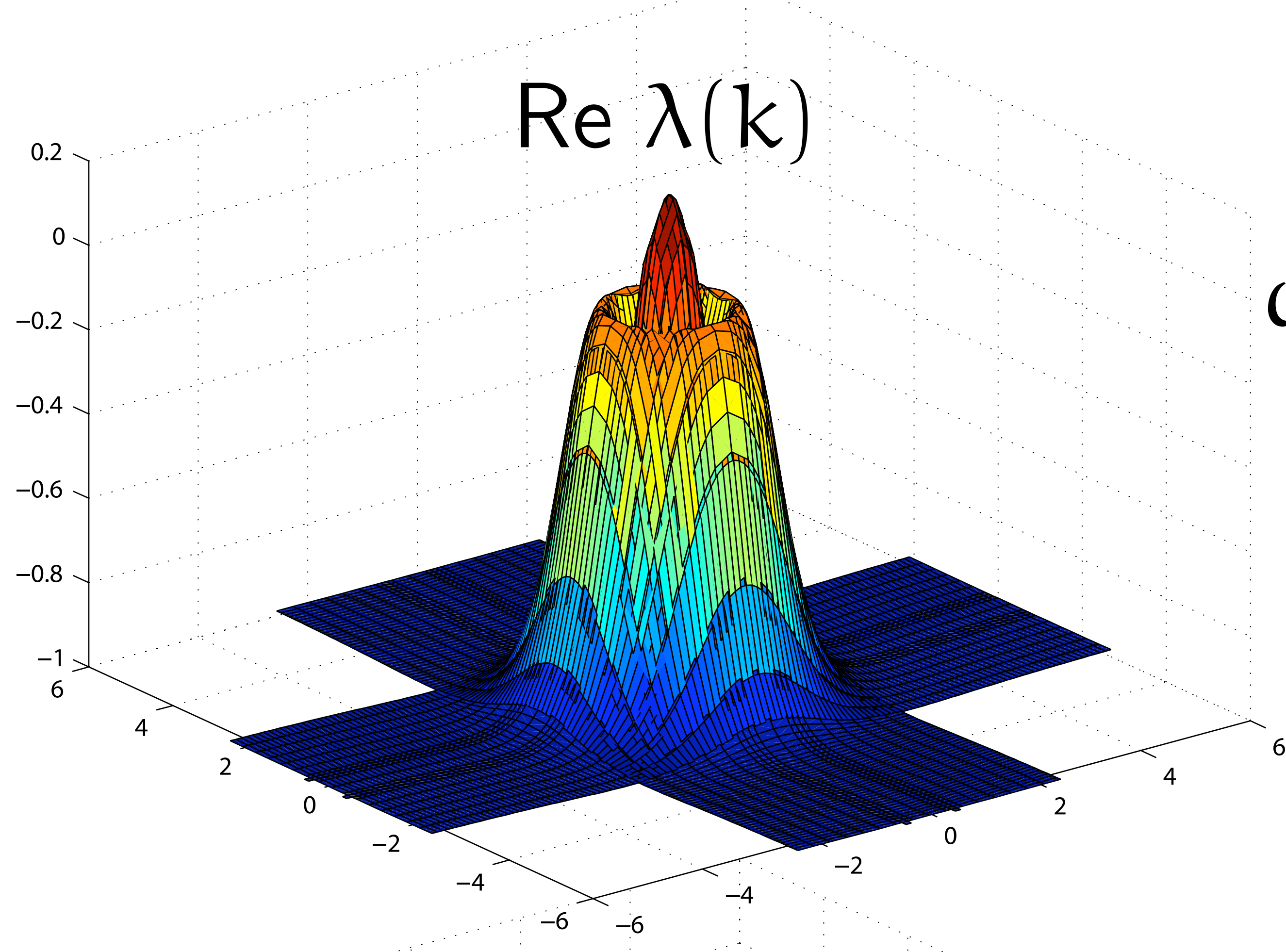
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
6
4
2
0
−2
−4
−6
−6
−4
−2
0
2
4
6


λ = ν + iω
ω
λ(k)
iω_c
0
−iω_c
0
ν


Re λ(k)
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
6
4
2
0
−2
−4
−6
λ = ν + iω
ω
λ(k)
iω_c
0
−iω_c
0
ν
γ
20
15
10
5
0
Turing-Hopf
Hopf
0
2
4
6
8
10
12
ν (axonal speed)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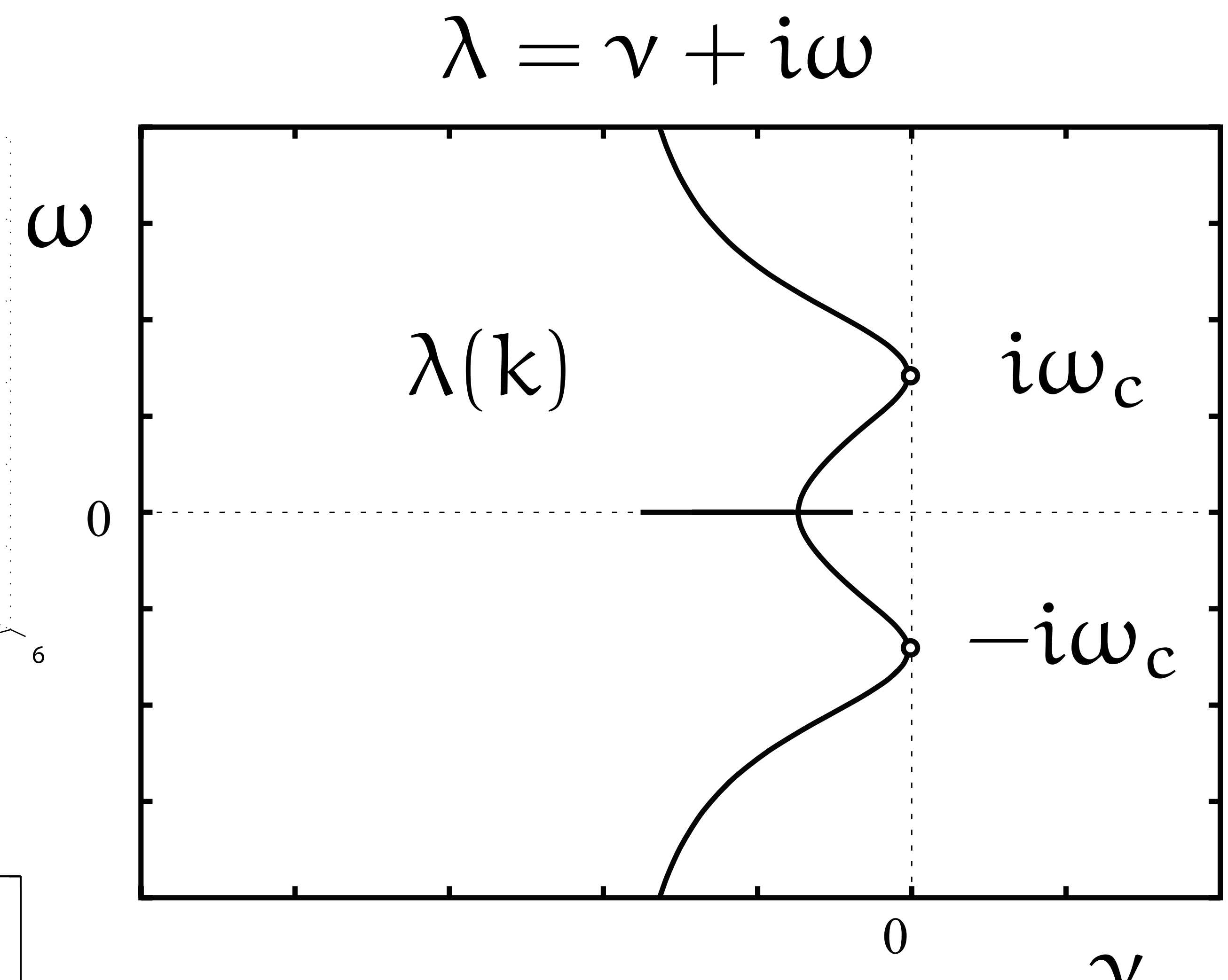
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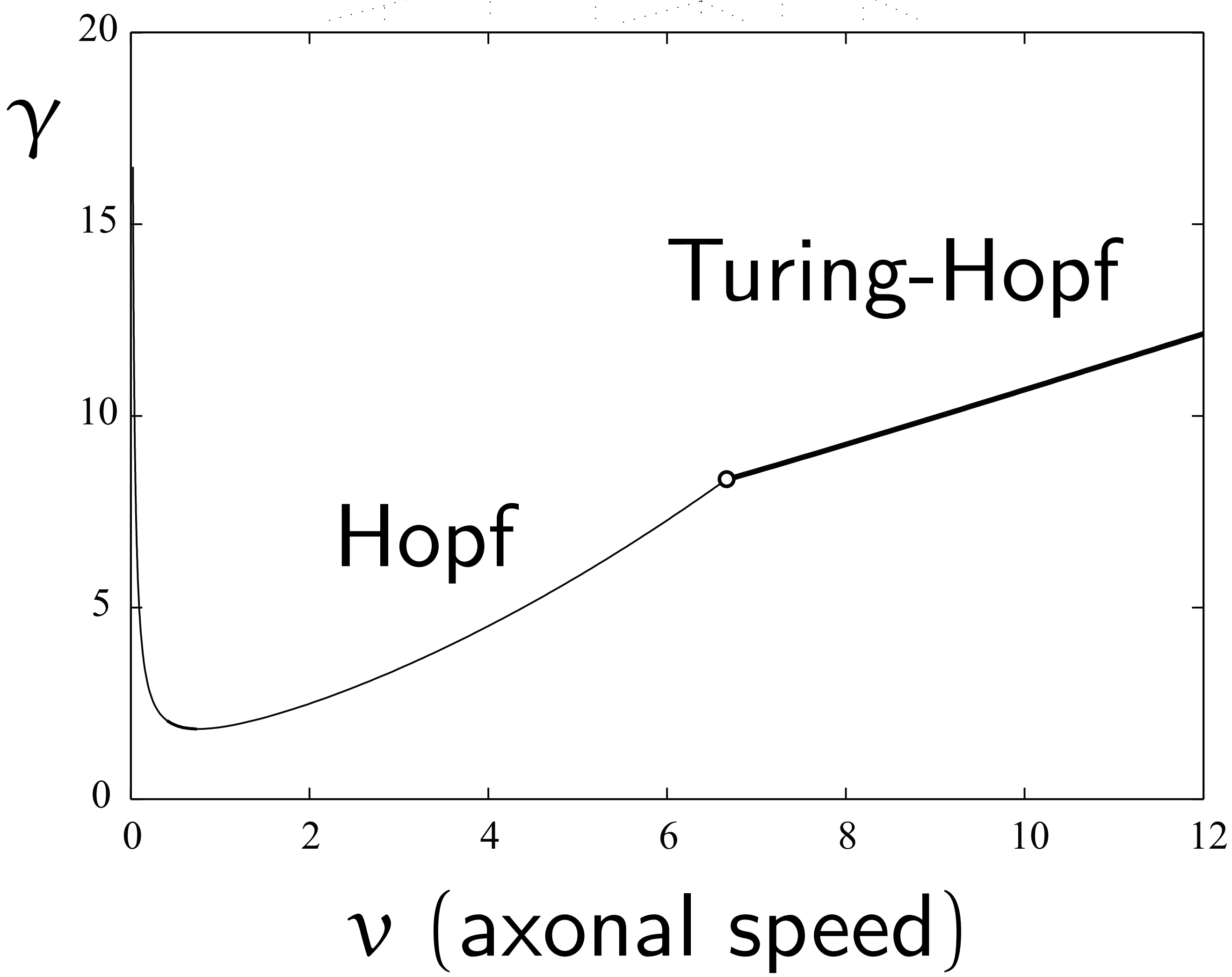
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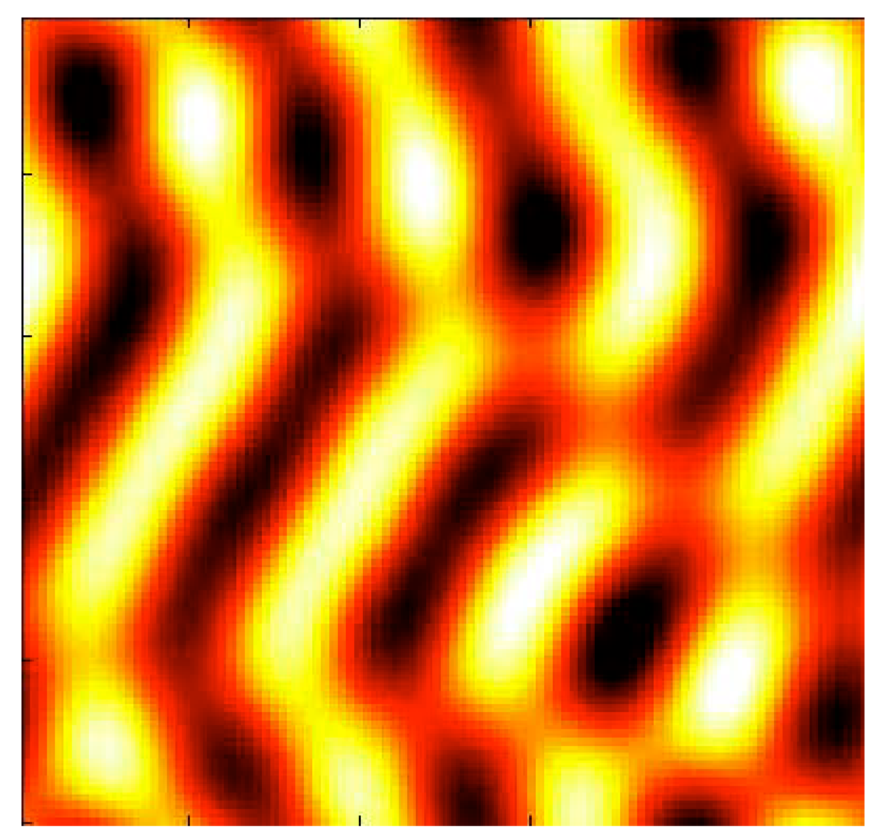

Amplitude Equations (one D)

Coupled mean-field Ginzburg–Landau equations describing a Turing–Hopf bifurcation with modulation group velocity of $O(1)$.

$$\frac{\partial A_1}{\partial \tau} = A_1(a + b|A_1|^2 + c\langle |A_2|^2 \rangle) + d\frac{\partial^2 A_1}{\partial \xi_+^2}$$

$$\frac{\partial A_2}{\partial \tau} = A_2(a + b|A_2|^2 + c\langle |A_1|^2 \rangle) + d\frac{\partial^2 A_2}{\partial \xi_-^2}$$

Coefficients in terms of integral transforms of w and η .

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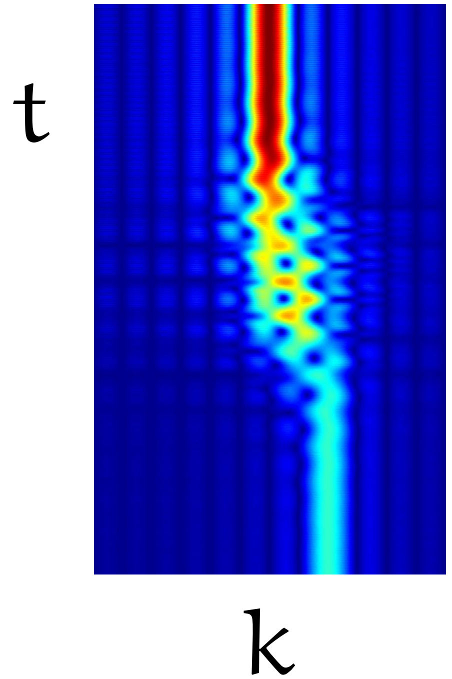

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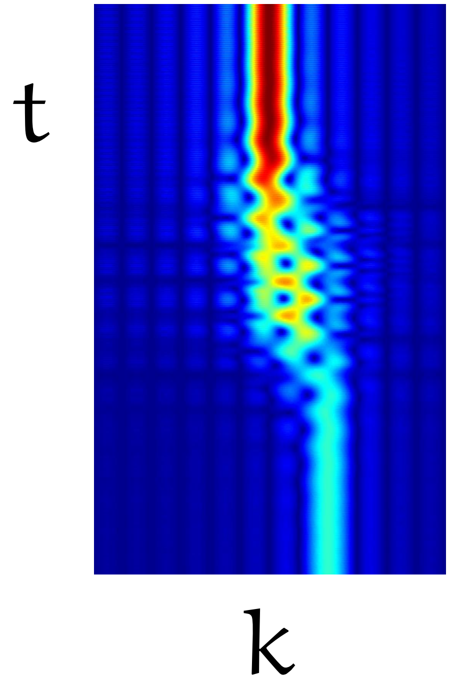
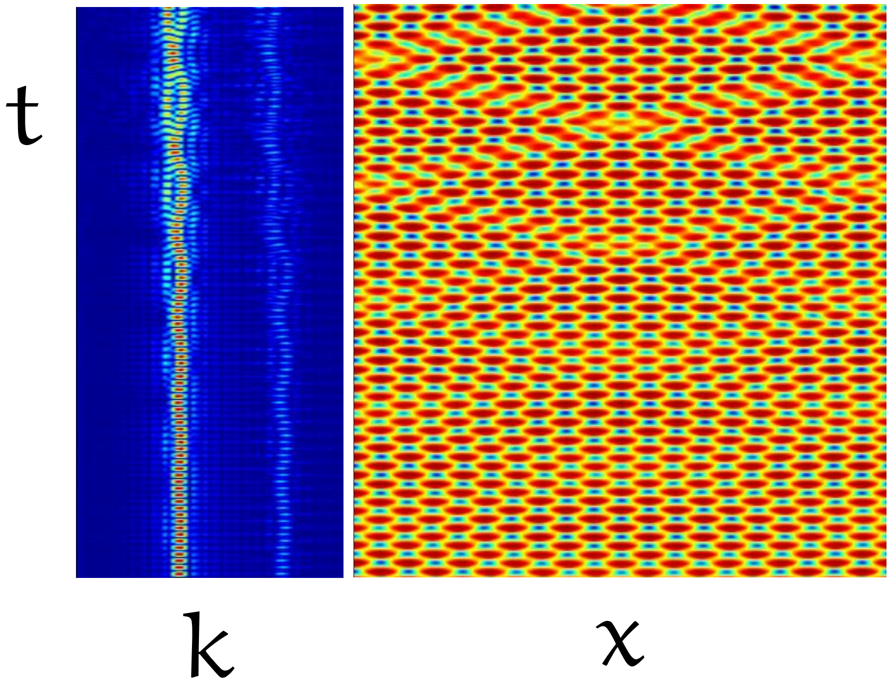


BF-Eckhaus instability



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Time independent localised solutions

$$w \otimes \eta * f \rightarrow w \otimes f$$

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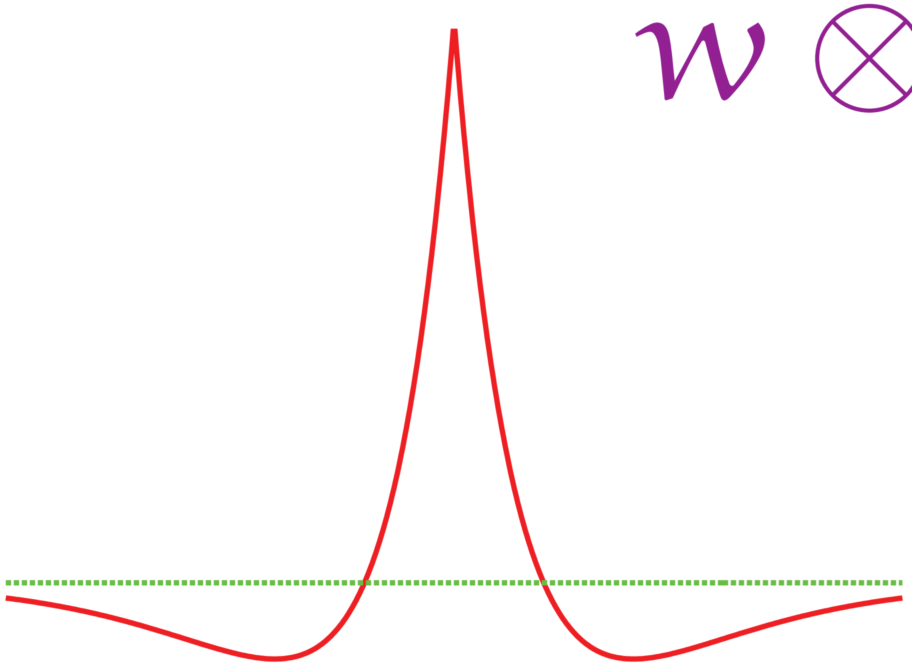

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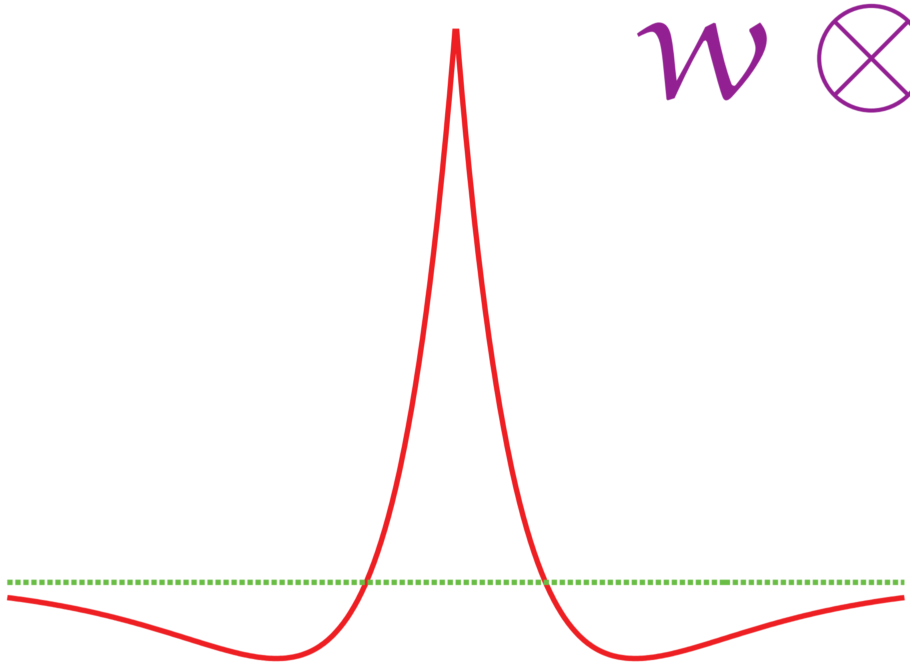

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$q(x)$

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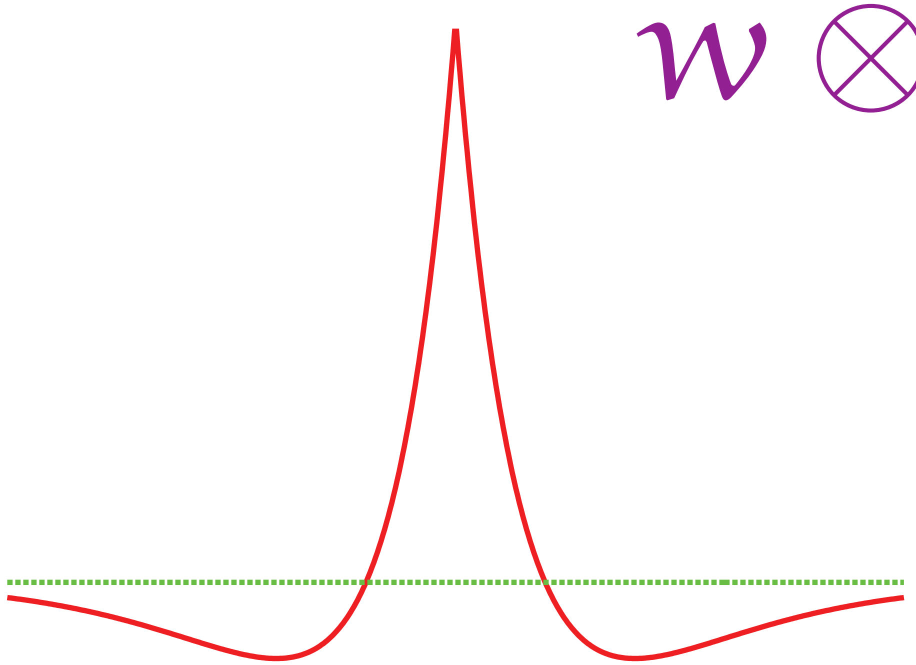

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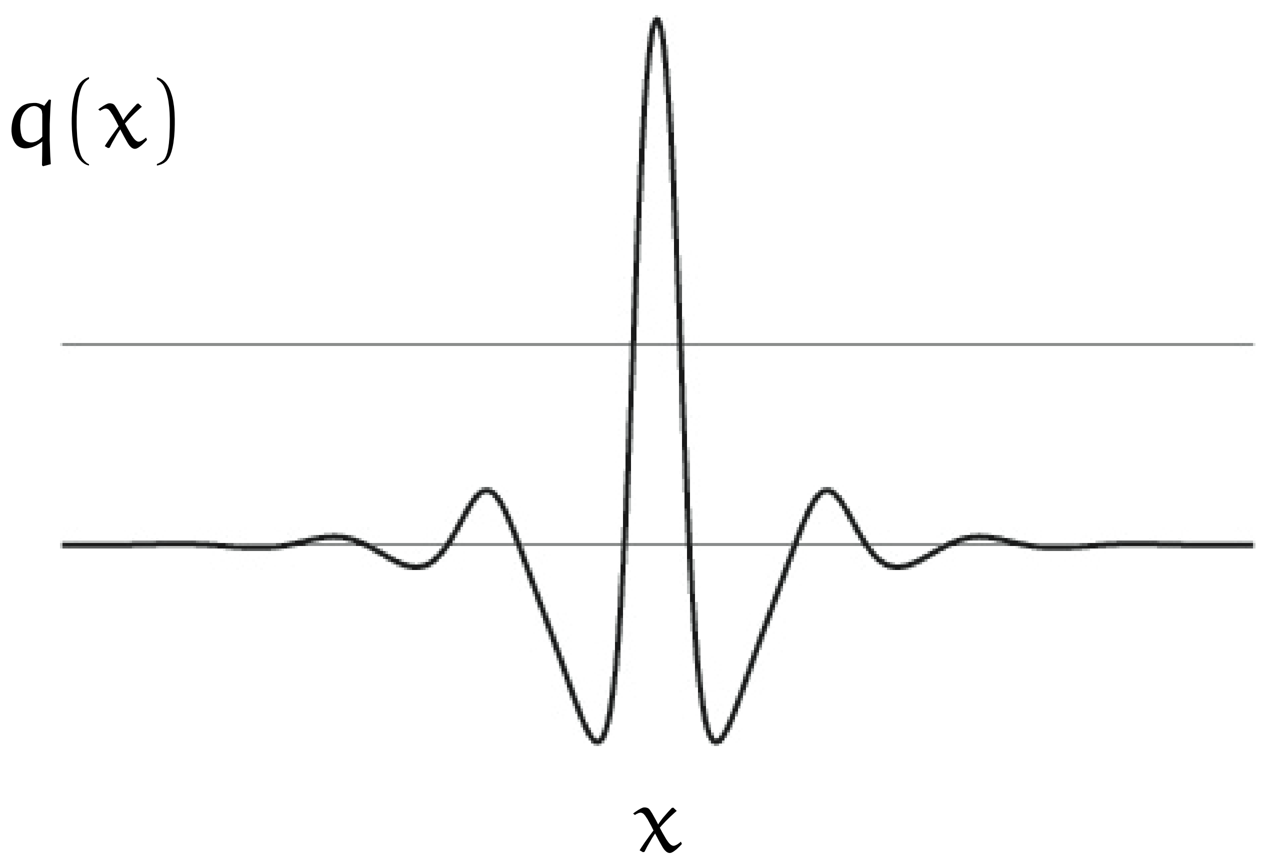

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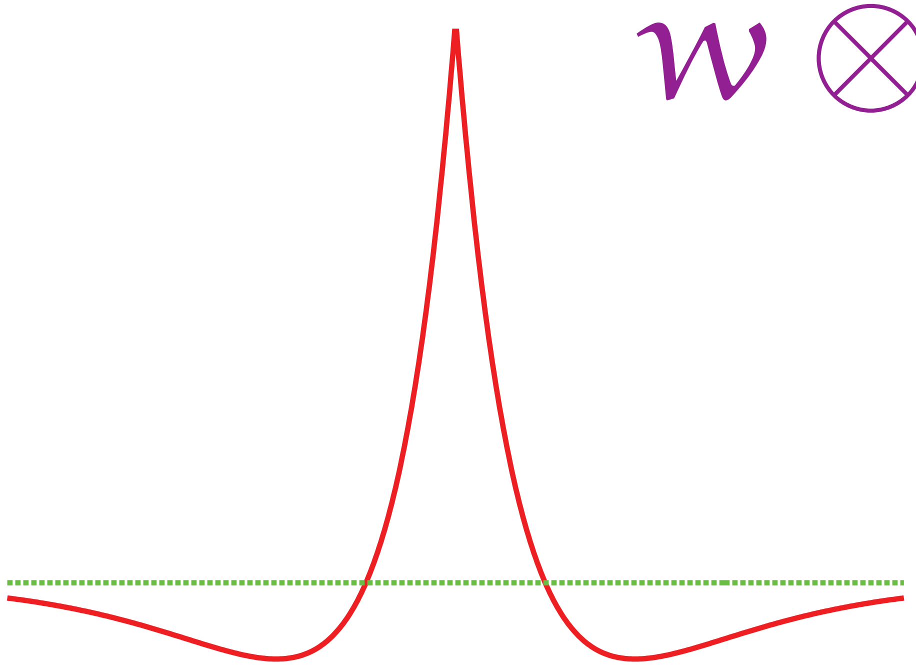

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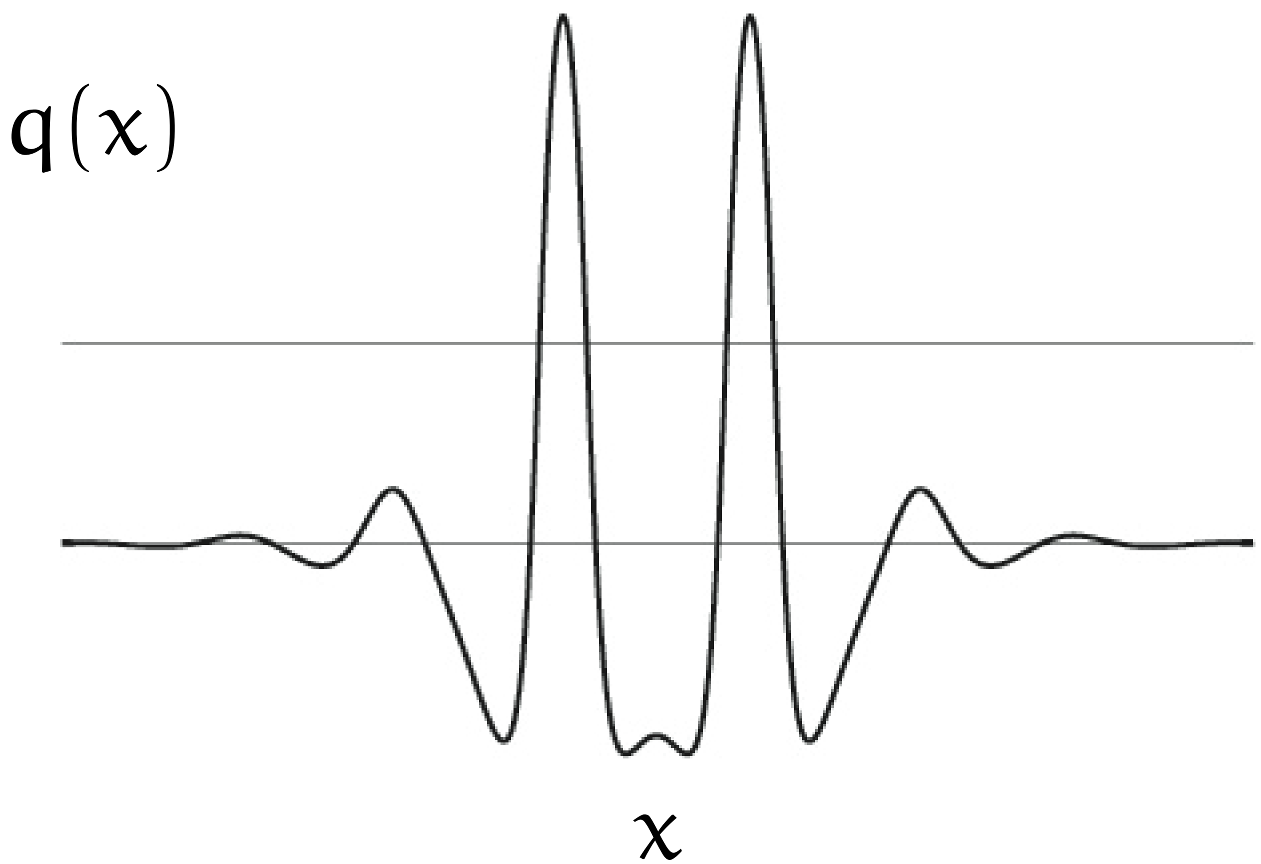

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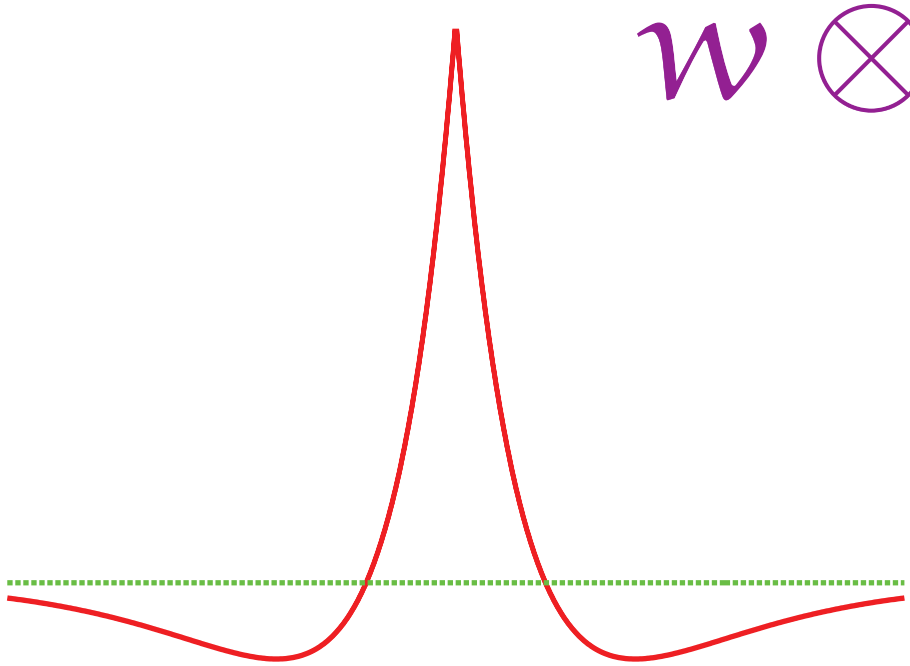

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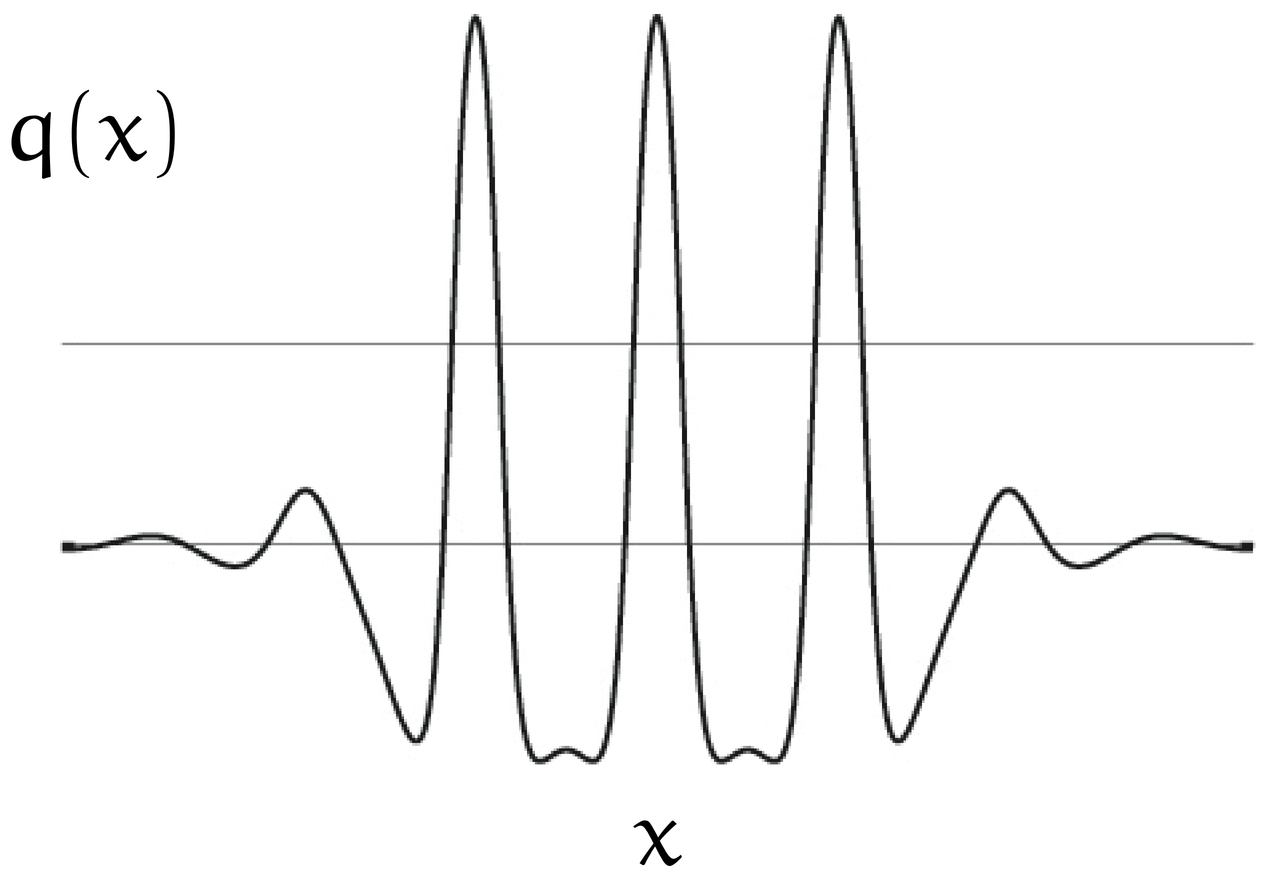

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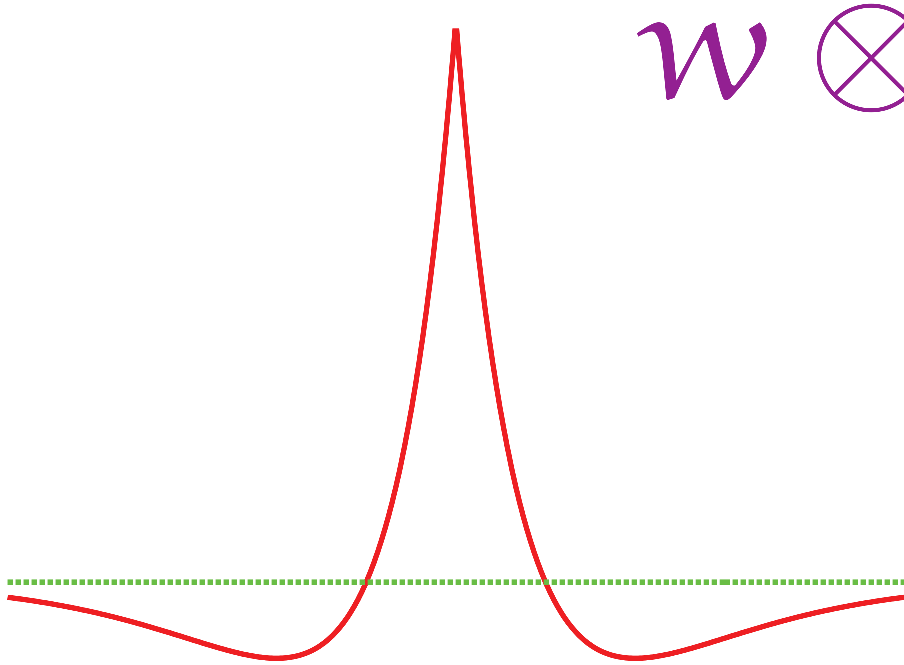

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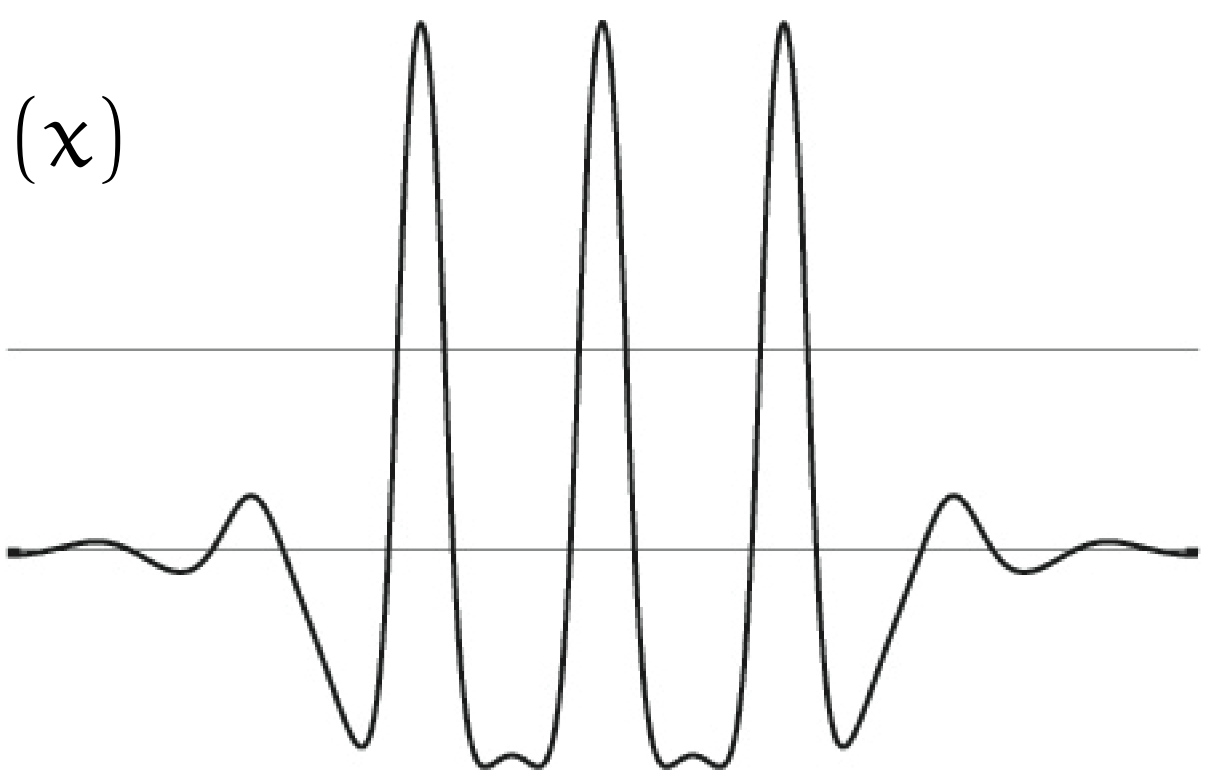

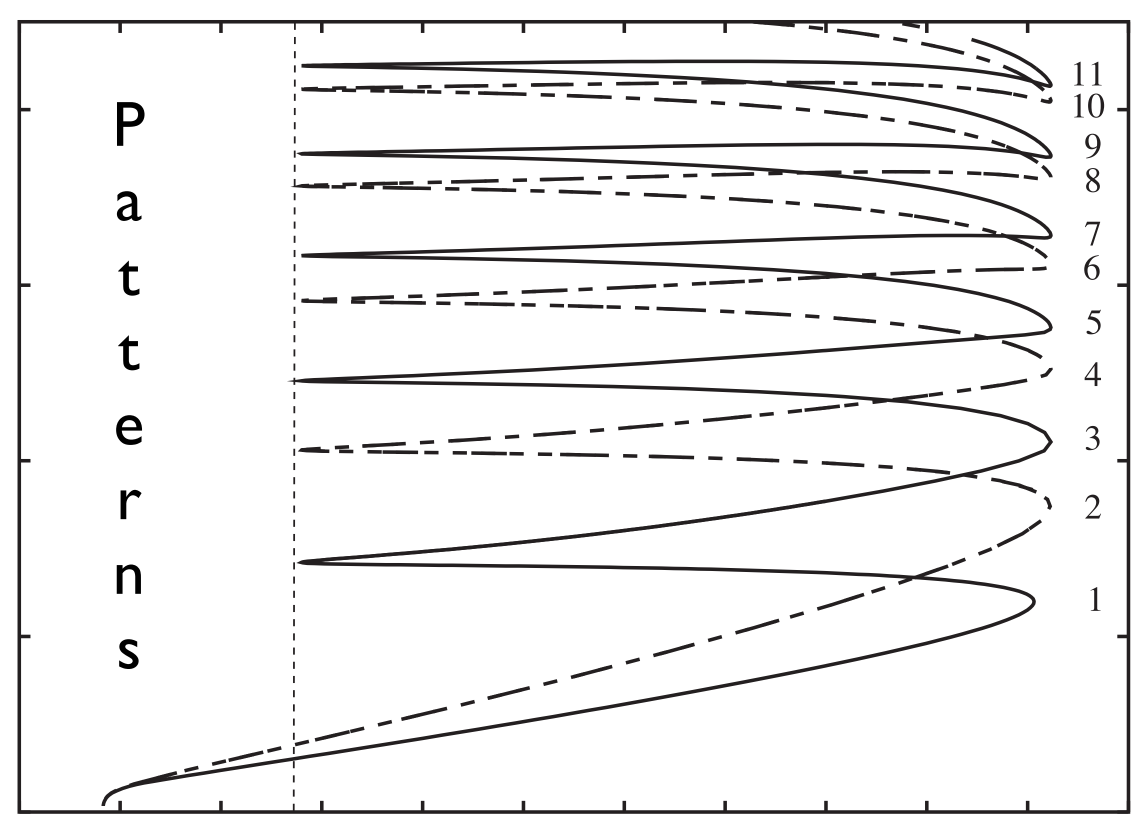

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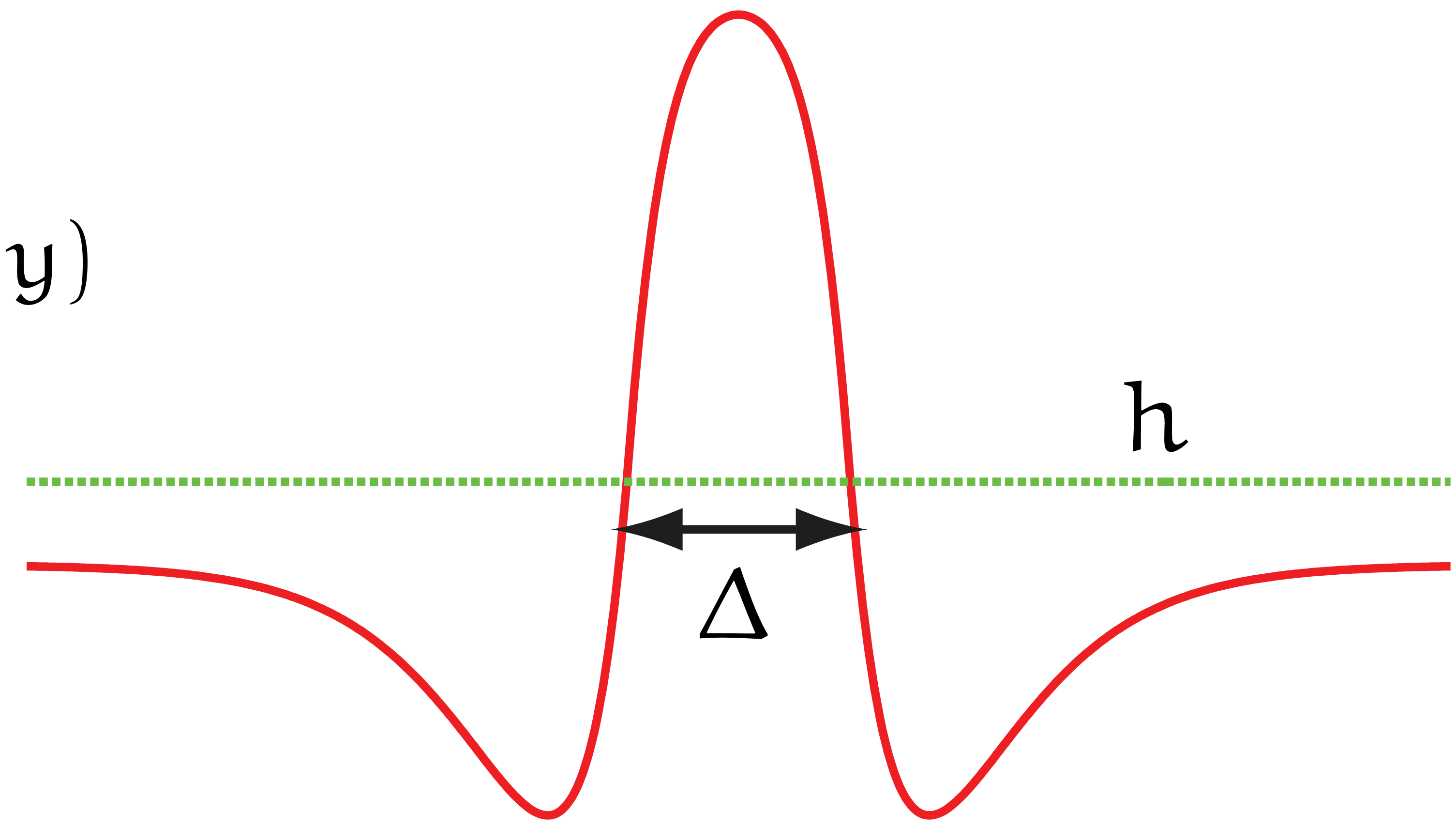

working memory

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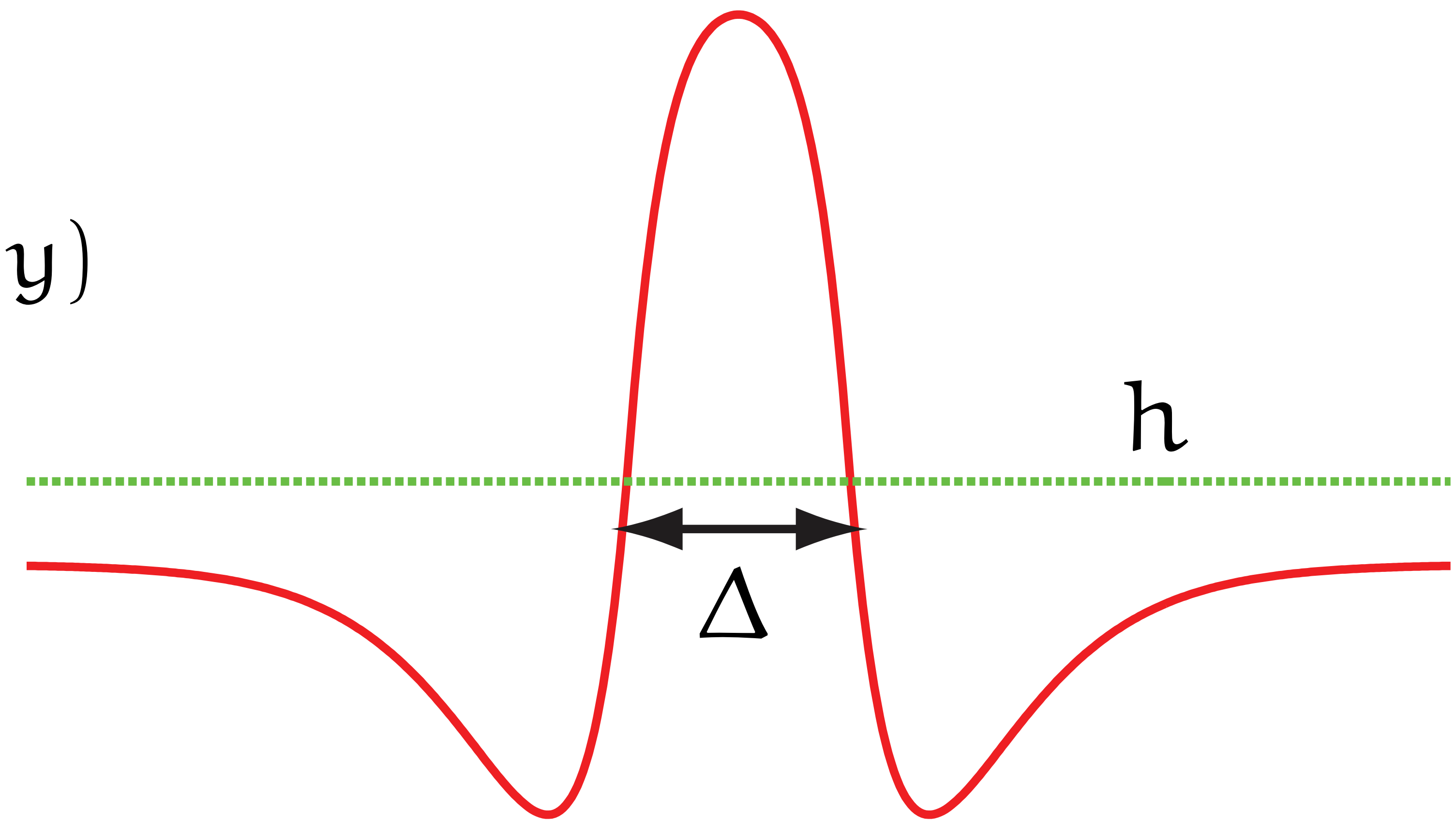

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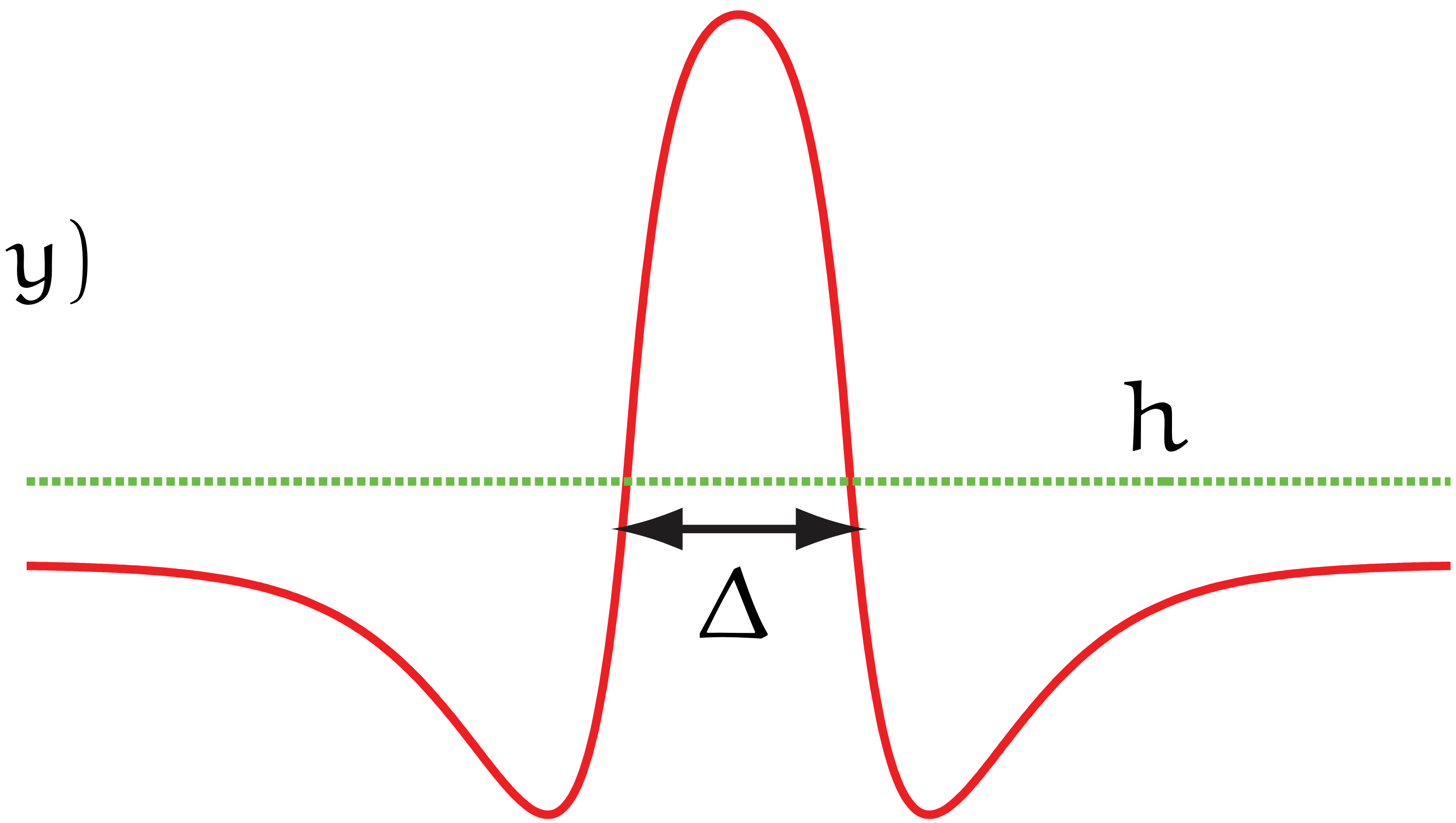

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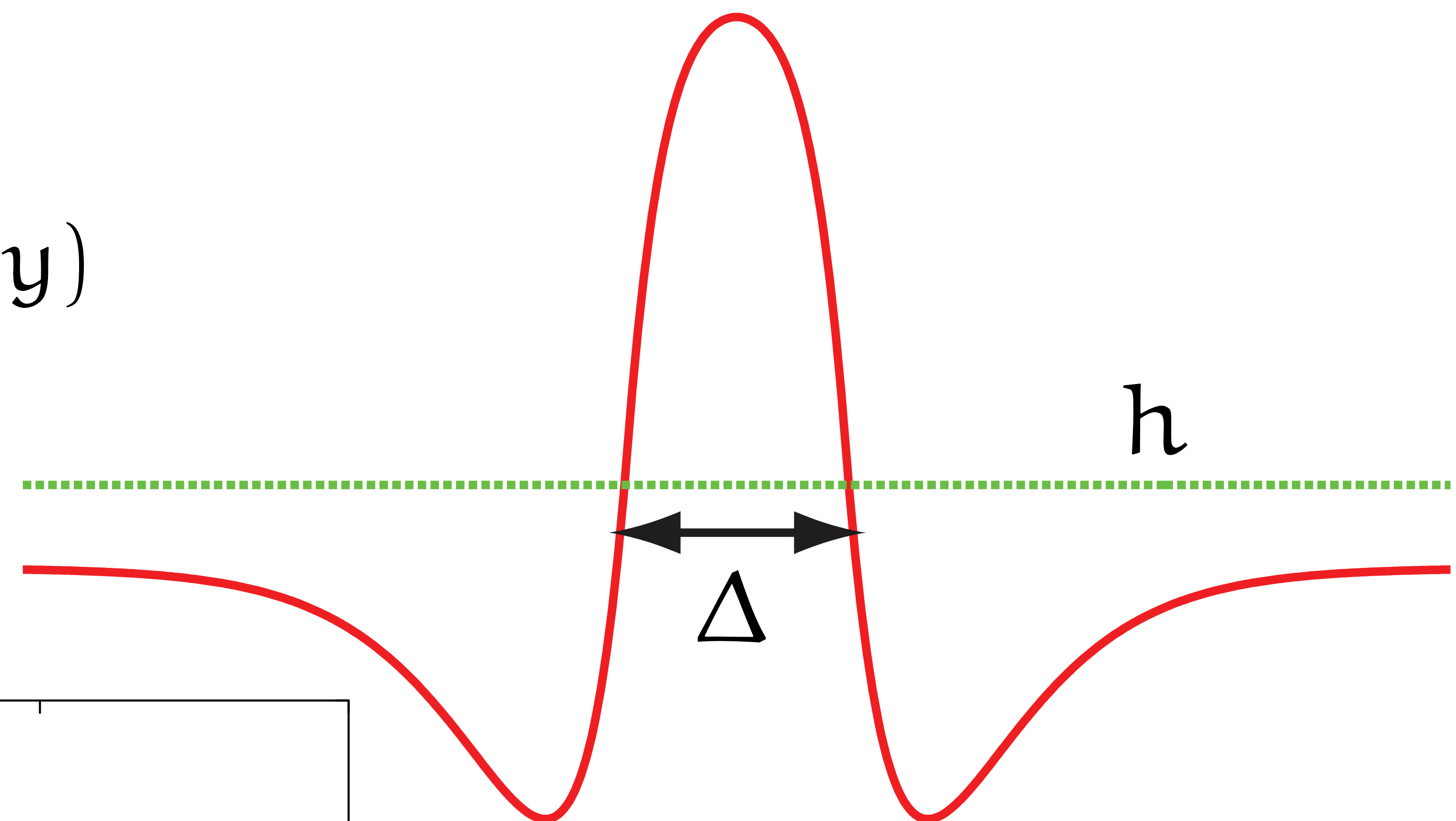

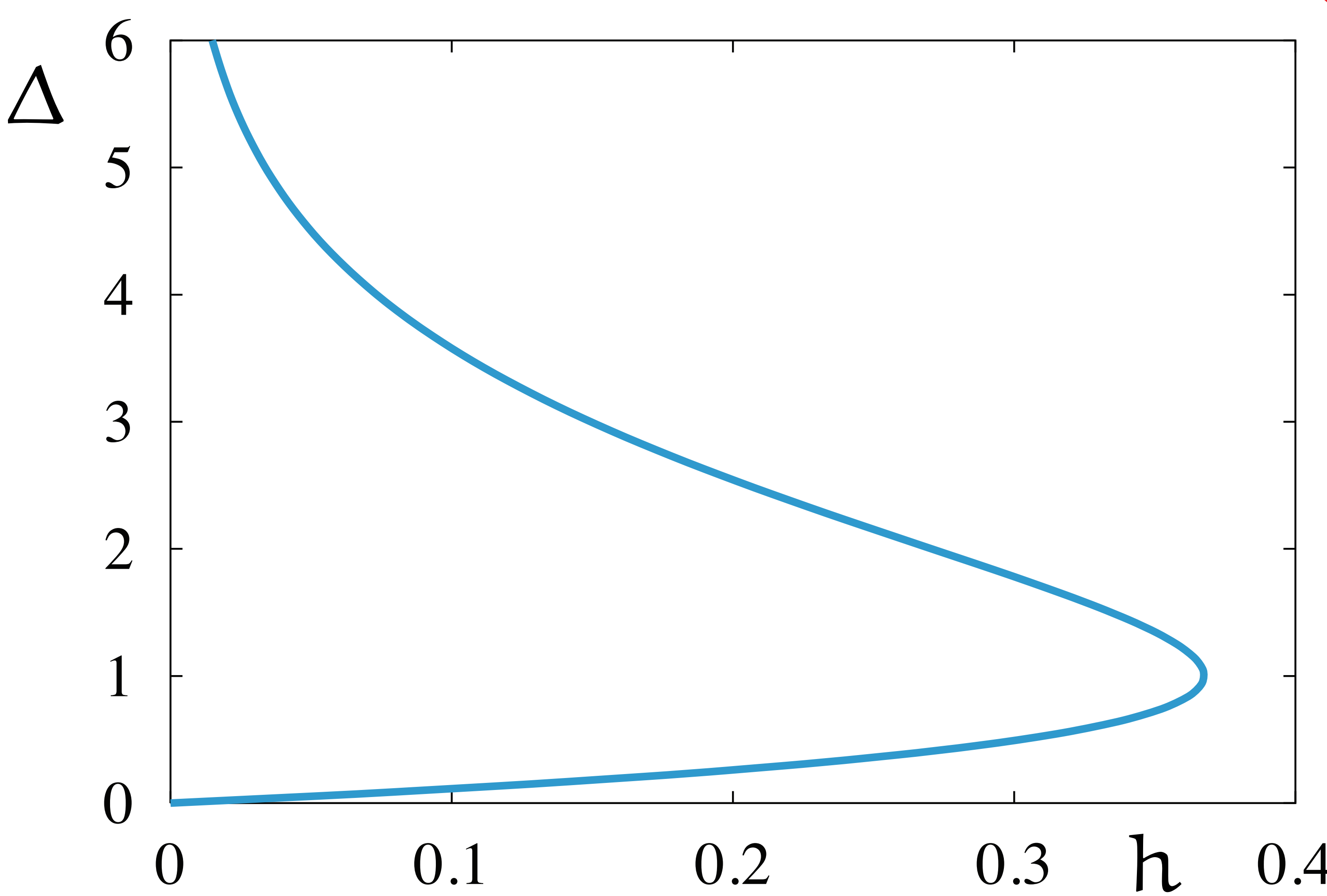

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For Heaviside firing rate

$$f'(q(x)) = \frac{\delta(x)}{|q'(0)|} + \frac{\delta(x-\Delta)}{|q'(\Delta)|}$$

so

$$u(x) = \frac{\tilde{\eta}(\lambda)}{|w(0) - w(\Delta)|} [w(x)u(0) + w(x-\Delta)u(\Delta)]$$

System of linear equations for perturbations at threshold

$$\begin{bmatrix} u(0) \\ u(\Delta) \end{bmatrix} = \mathcal{A}(\lambda) \begin{bmatrix} u(0) \\ u(\Delta) \end{bmatrix}, \qquad \mathcal{A}(\lambda) = \frac{\widetilde{\eta}(\lambda)}{|w(0) - w(\Delta)|} \begin{bmatrix} w(0) & w(\Delta) \\ w(\Delta) & w(0) \end{bmatrix}$$

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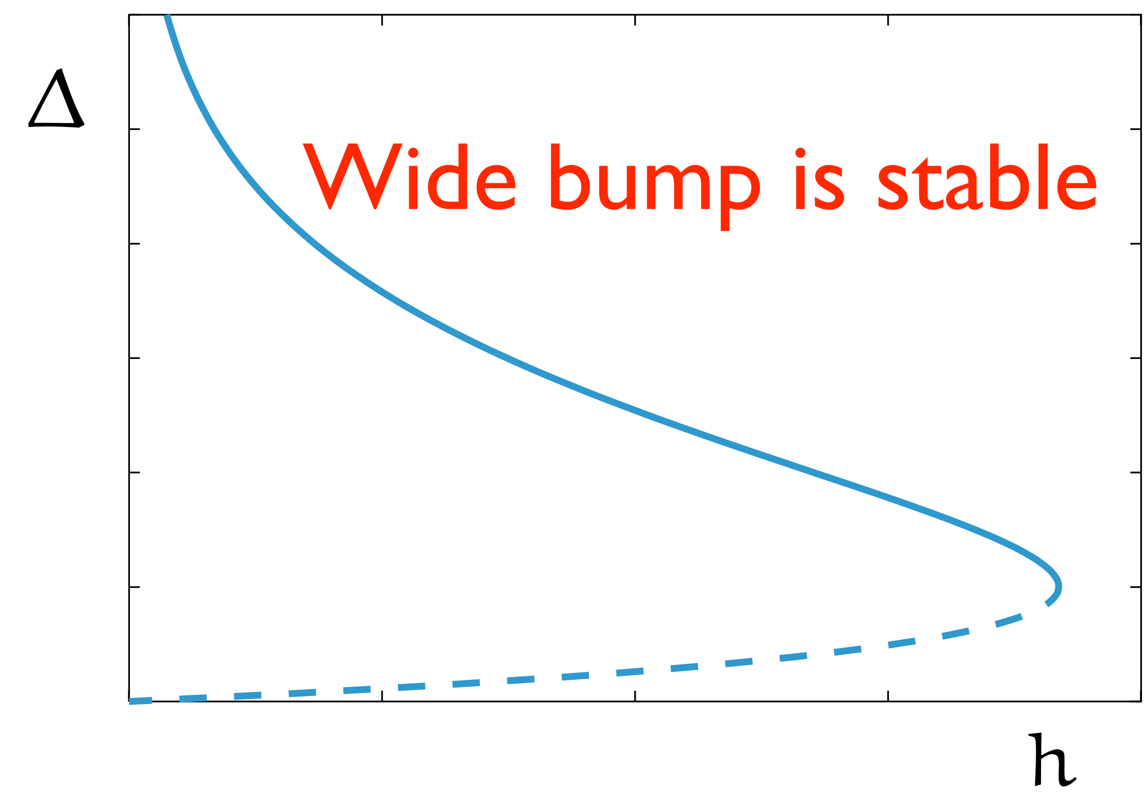
Solutions stable if Re $\lambda < 0$



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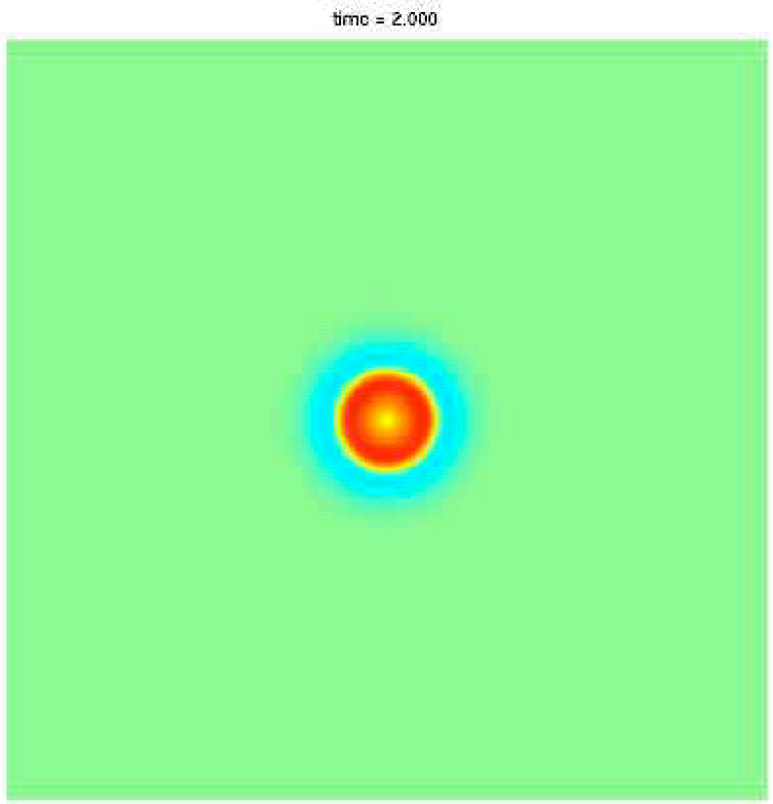
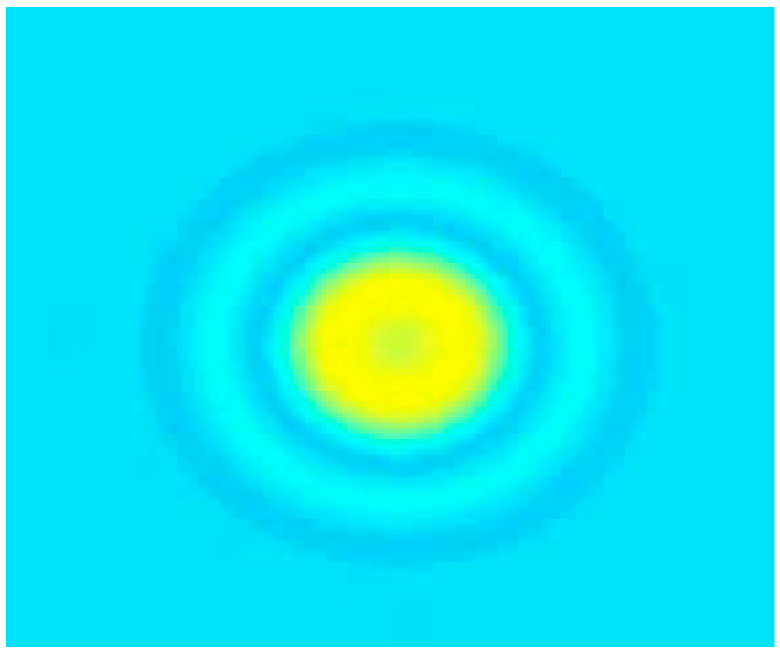
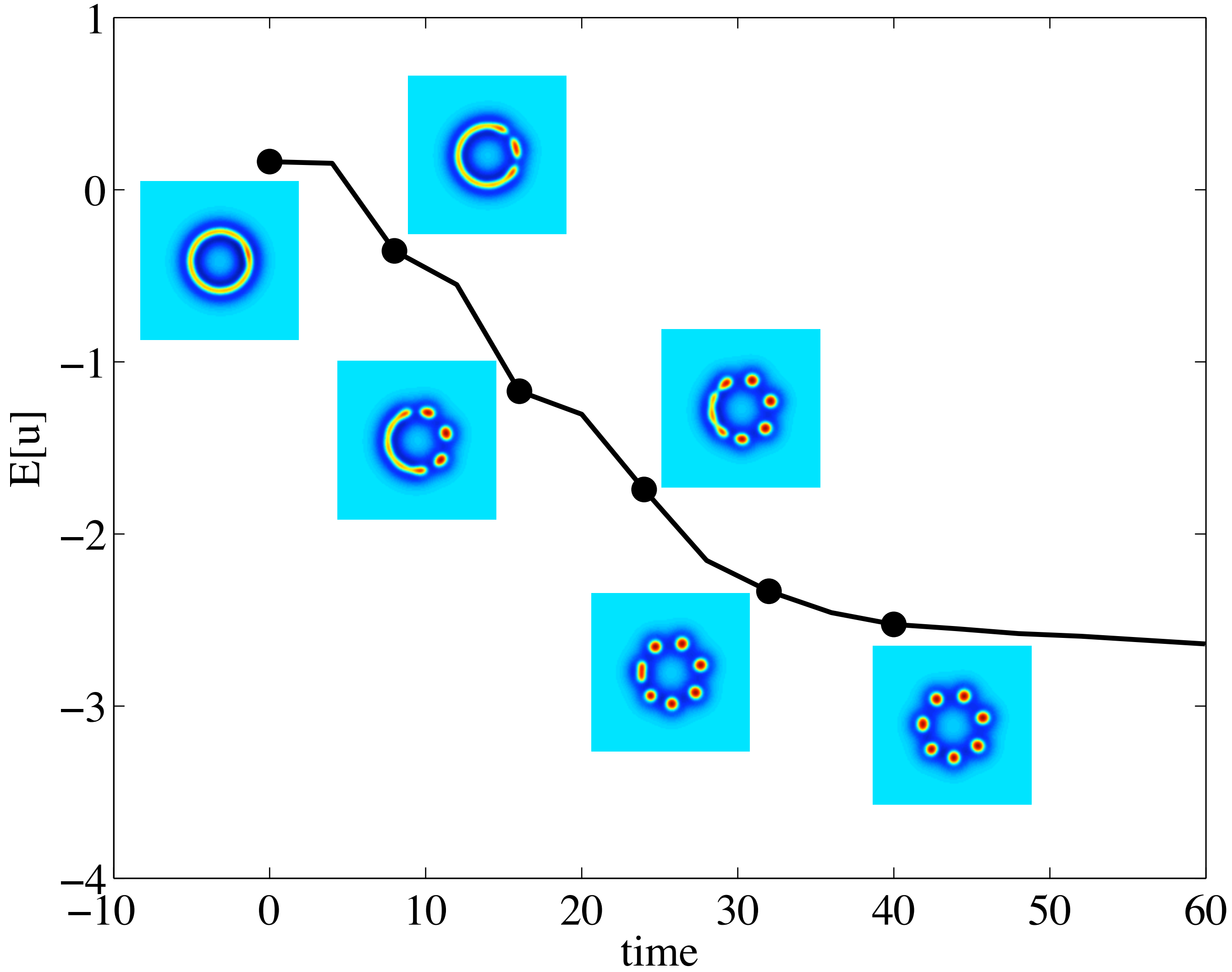
Predictions of Evans function







M R Owen, C R Laing and S Coombes 2007 Bumps and rings in a two-dimensional neural field: splitting and rotational instabilities, New Journal of Physics, Vol 9, 378

Threshold accommodation

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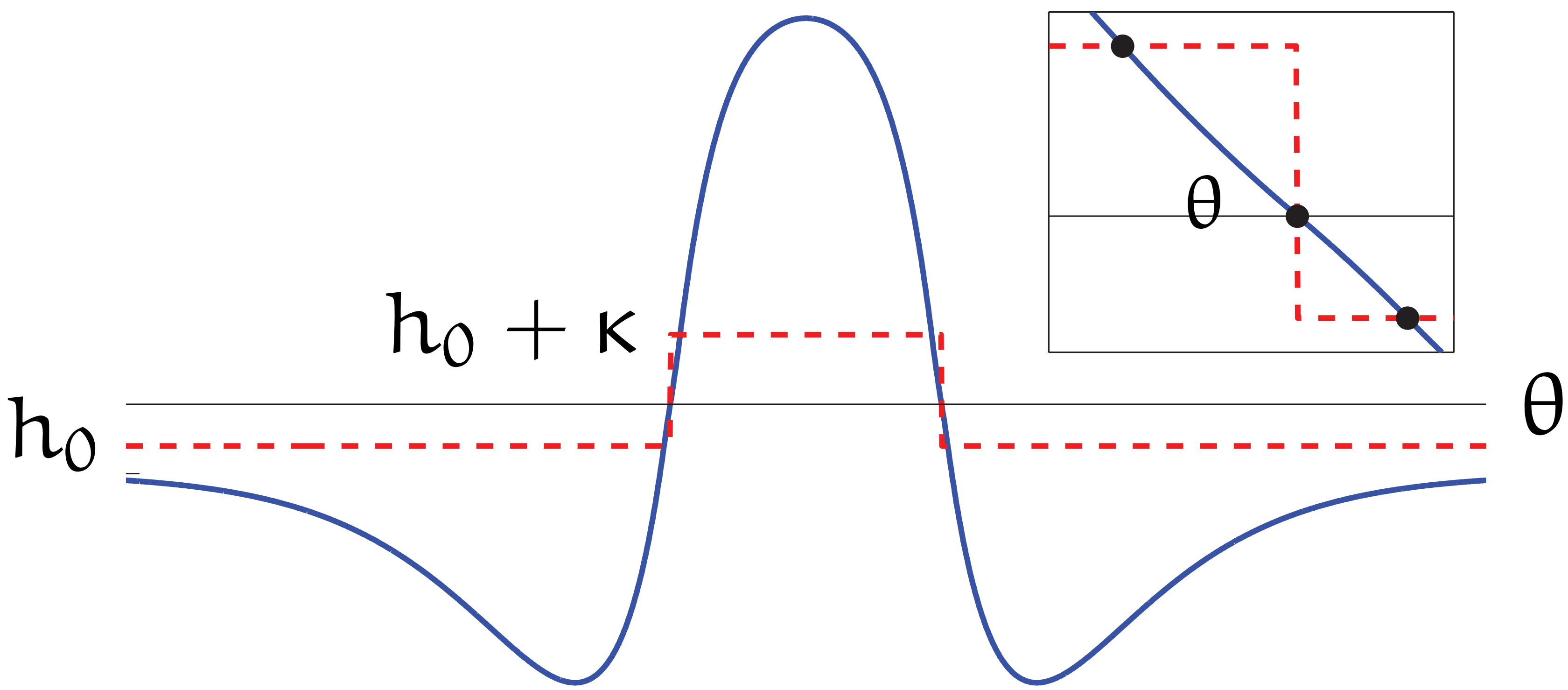
One bump $(u, h) = (q(x), p(x))$

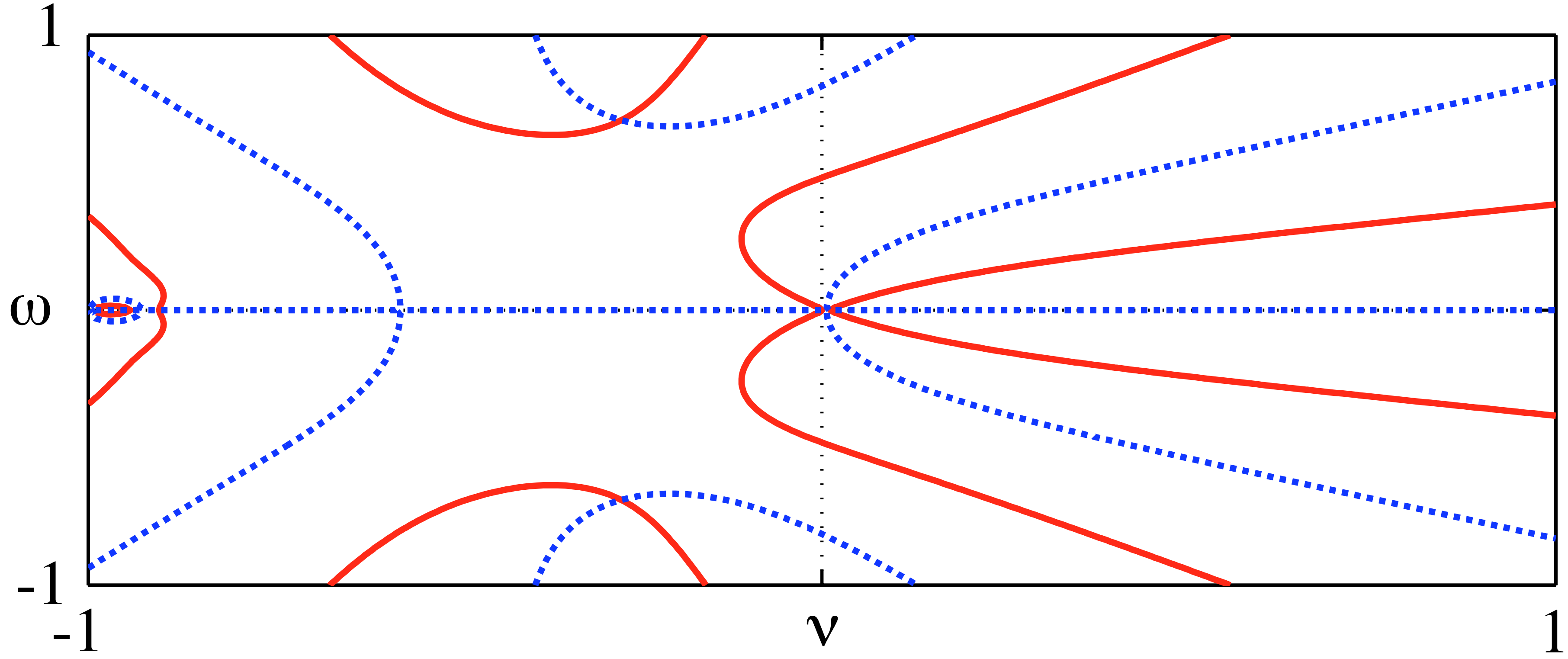
$$q = w \otimes H(q - p)$$

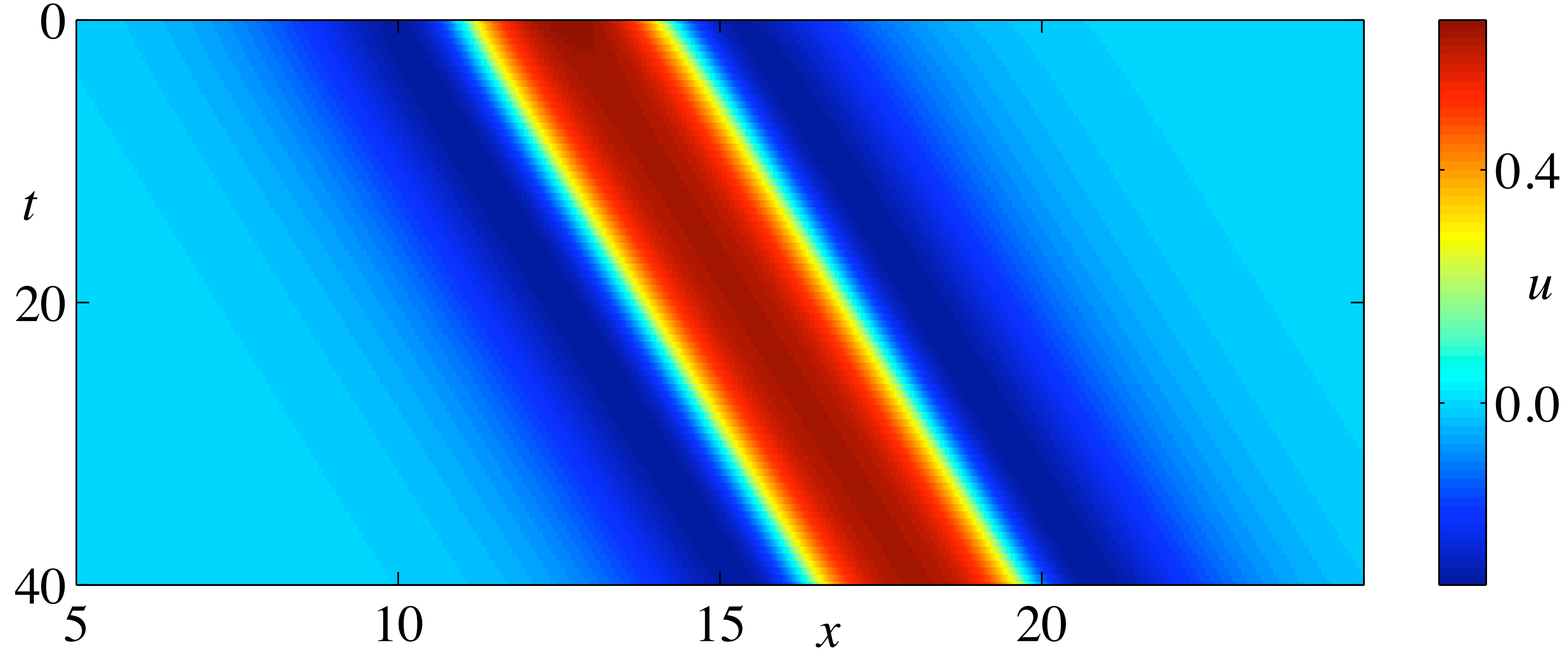
$$p = \begin{cases} h_0 & q < \theta \\ h_0 + \kappa & q \geq \theta \end{cases}$$



Bump Stability I: $\eta(t) = \alpha^2 t e^{-\alpha t}$

Low κ instability on Re axis (increasing α)





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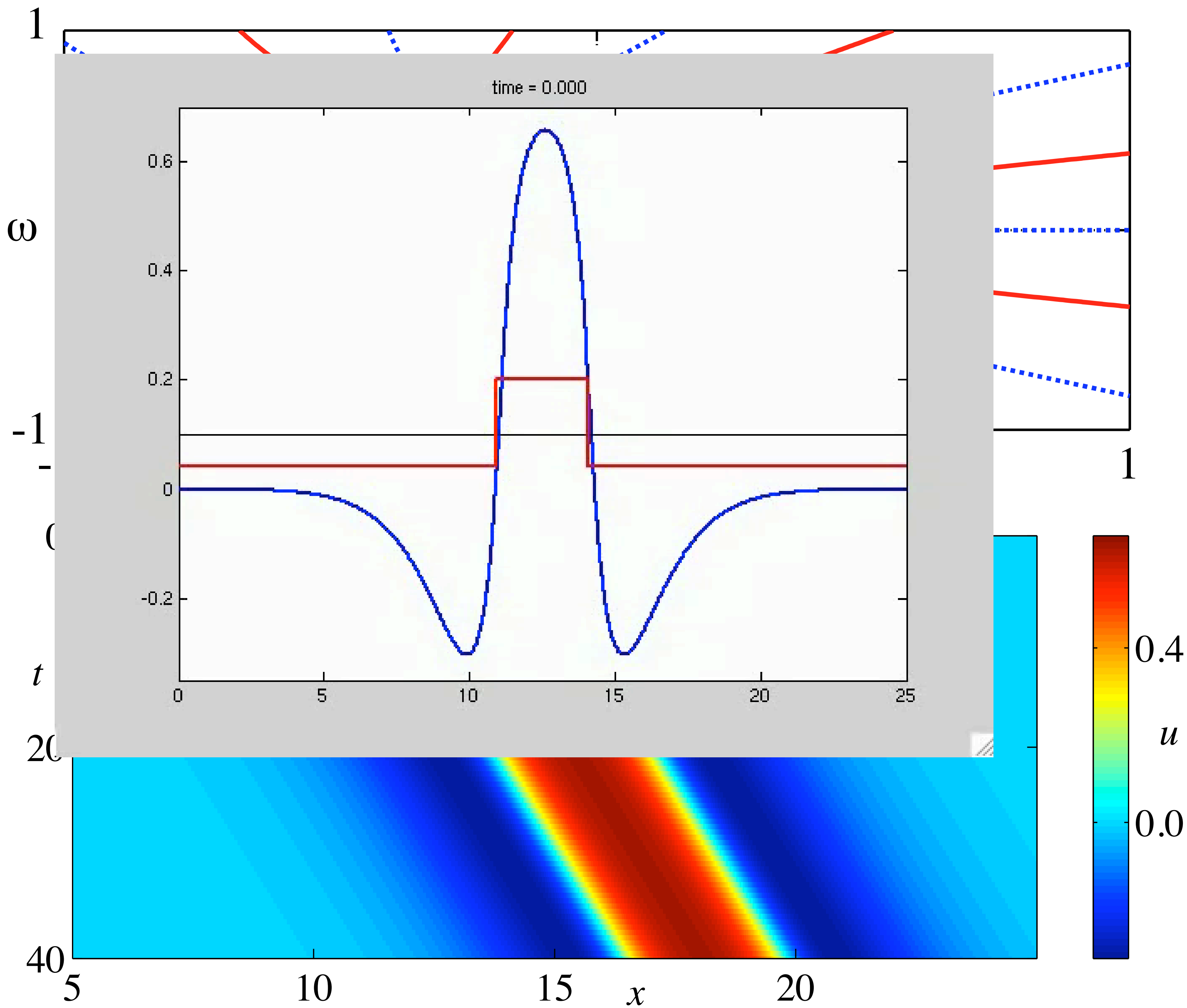

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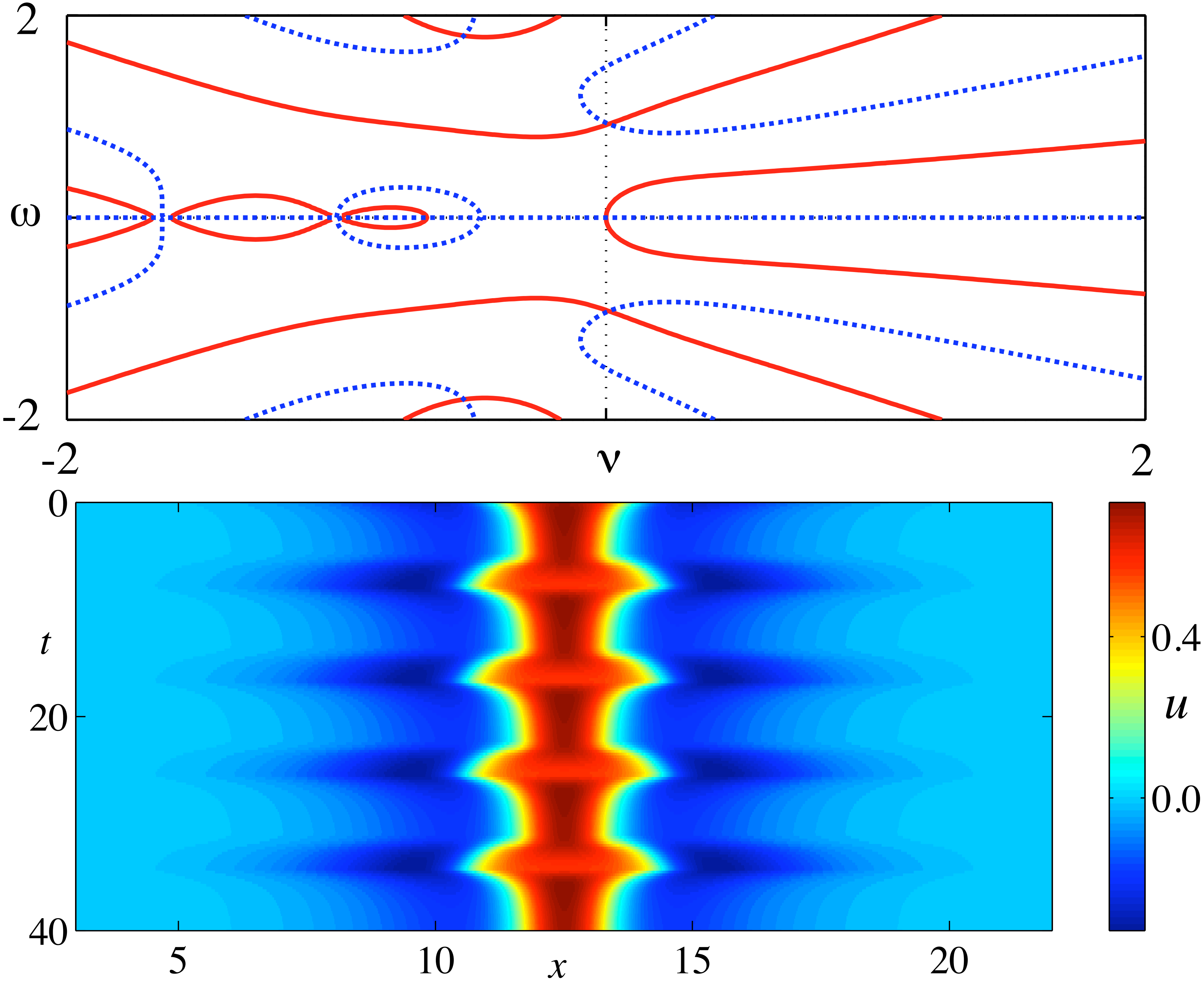

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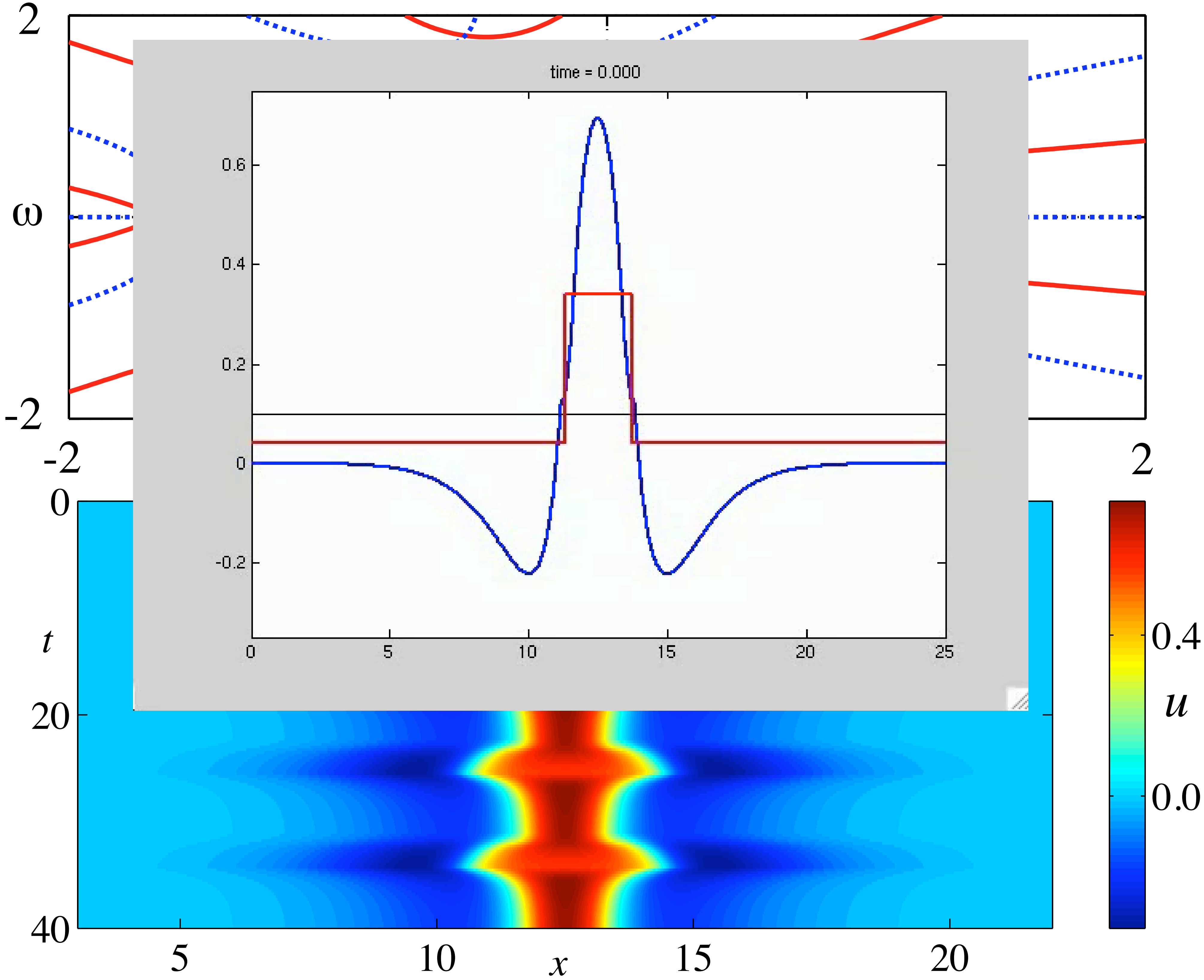
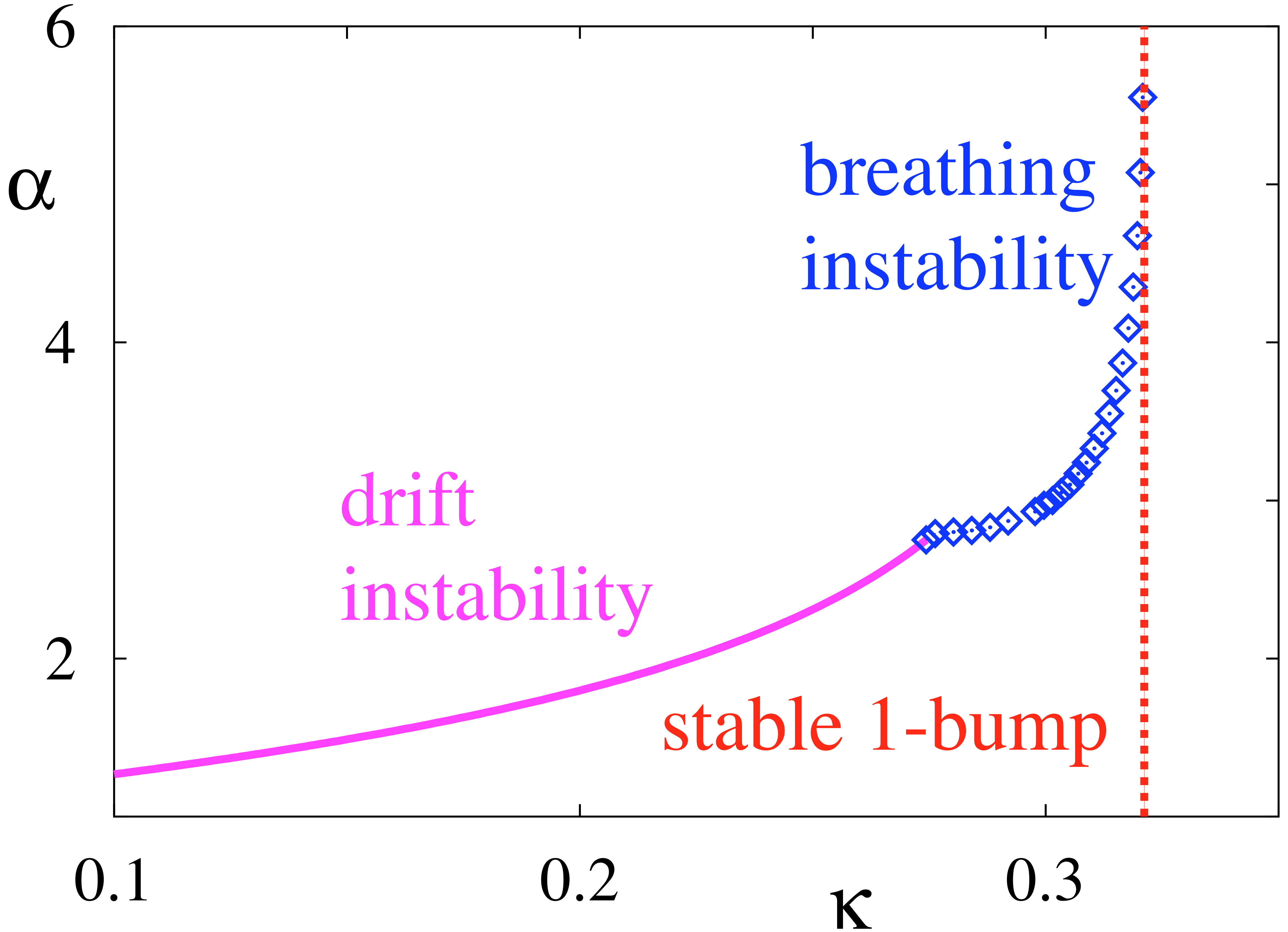


Summary of Bump instabilities



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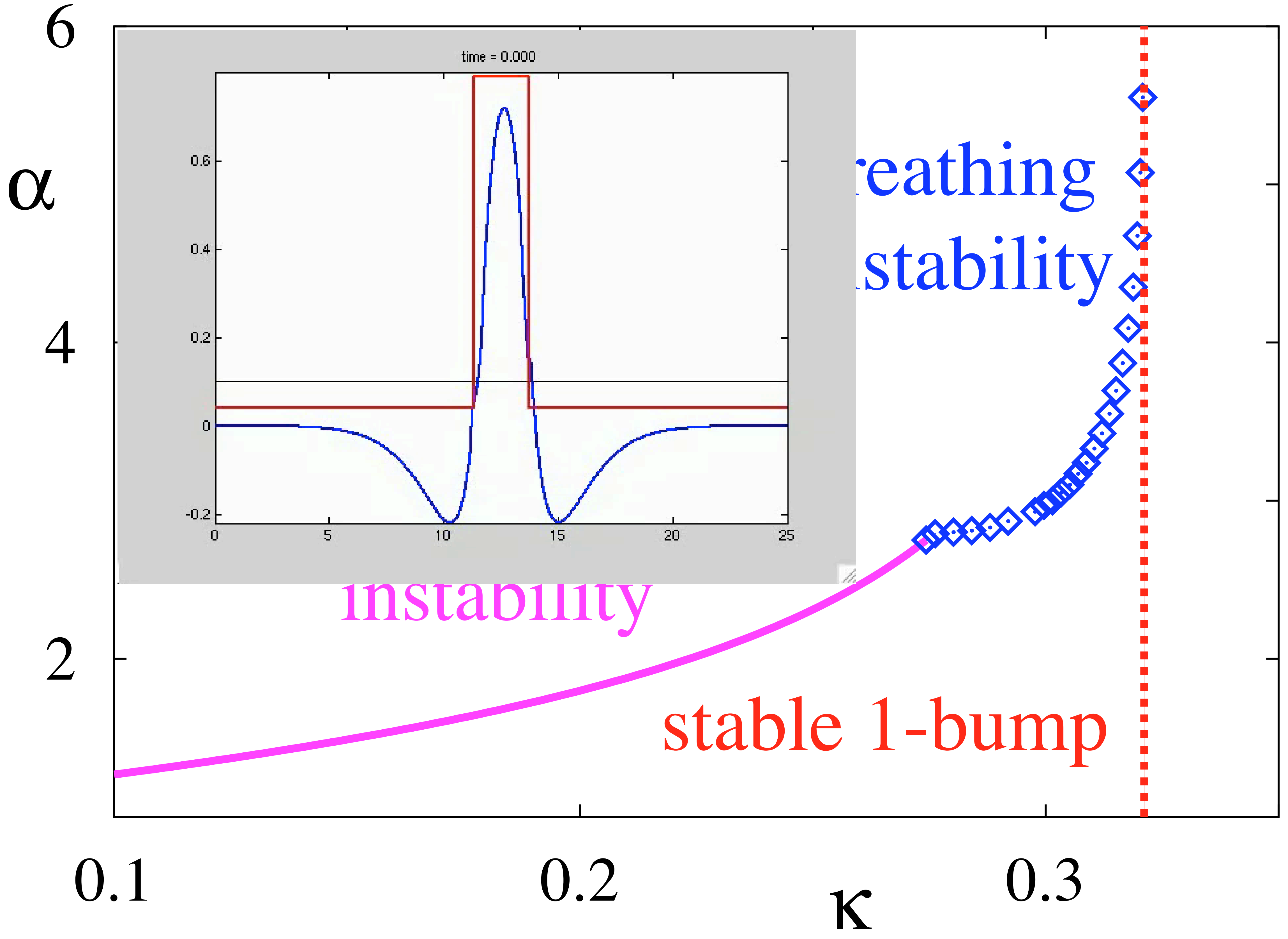
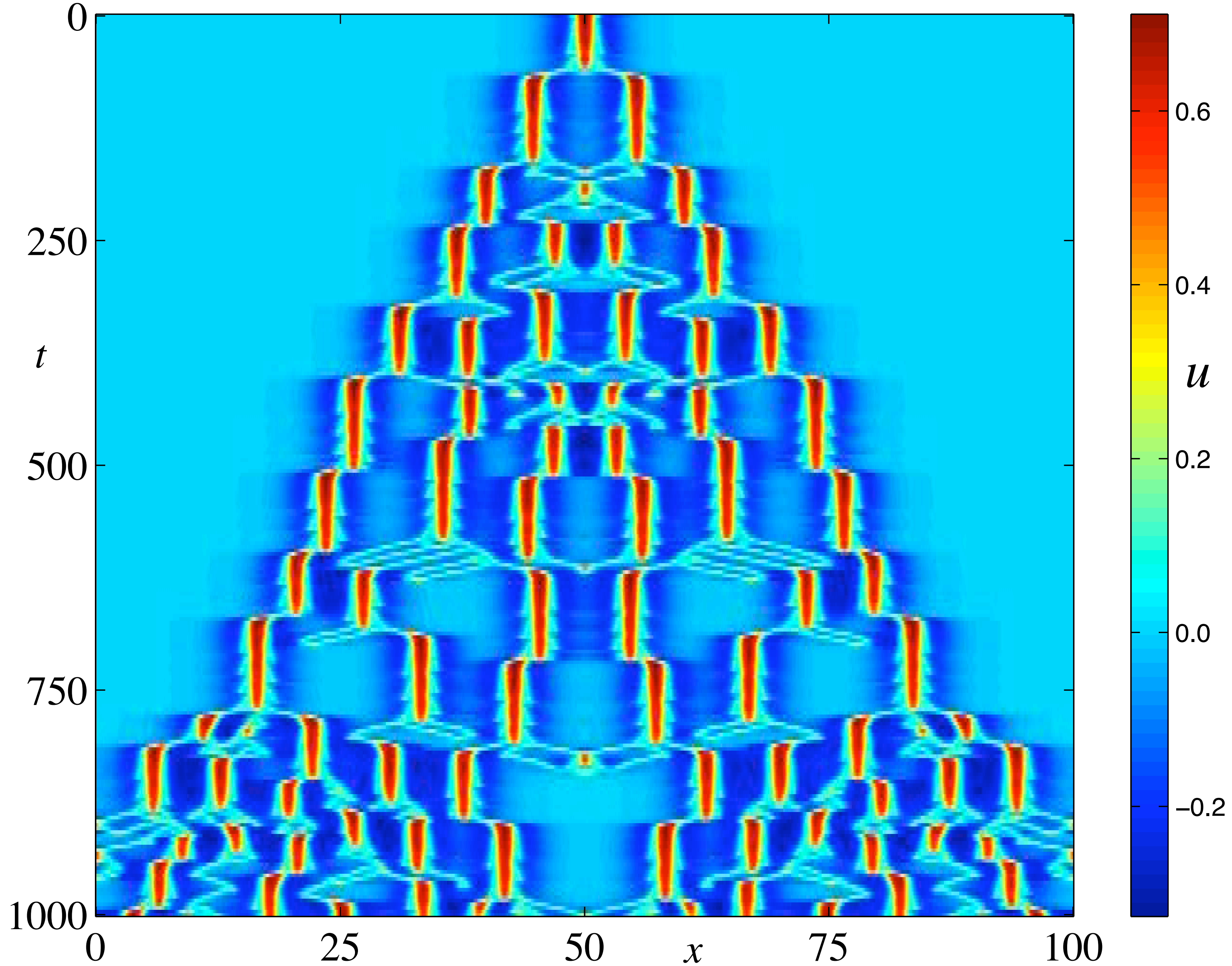


Exotic Dynamics

... including asymmetric breathers, multiple bumps, multiple pulses, periodic traveling waves, and bump-splitting instabilities that appear to lead to spatio-temporal chaos.



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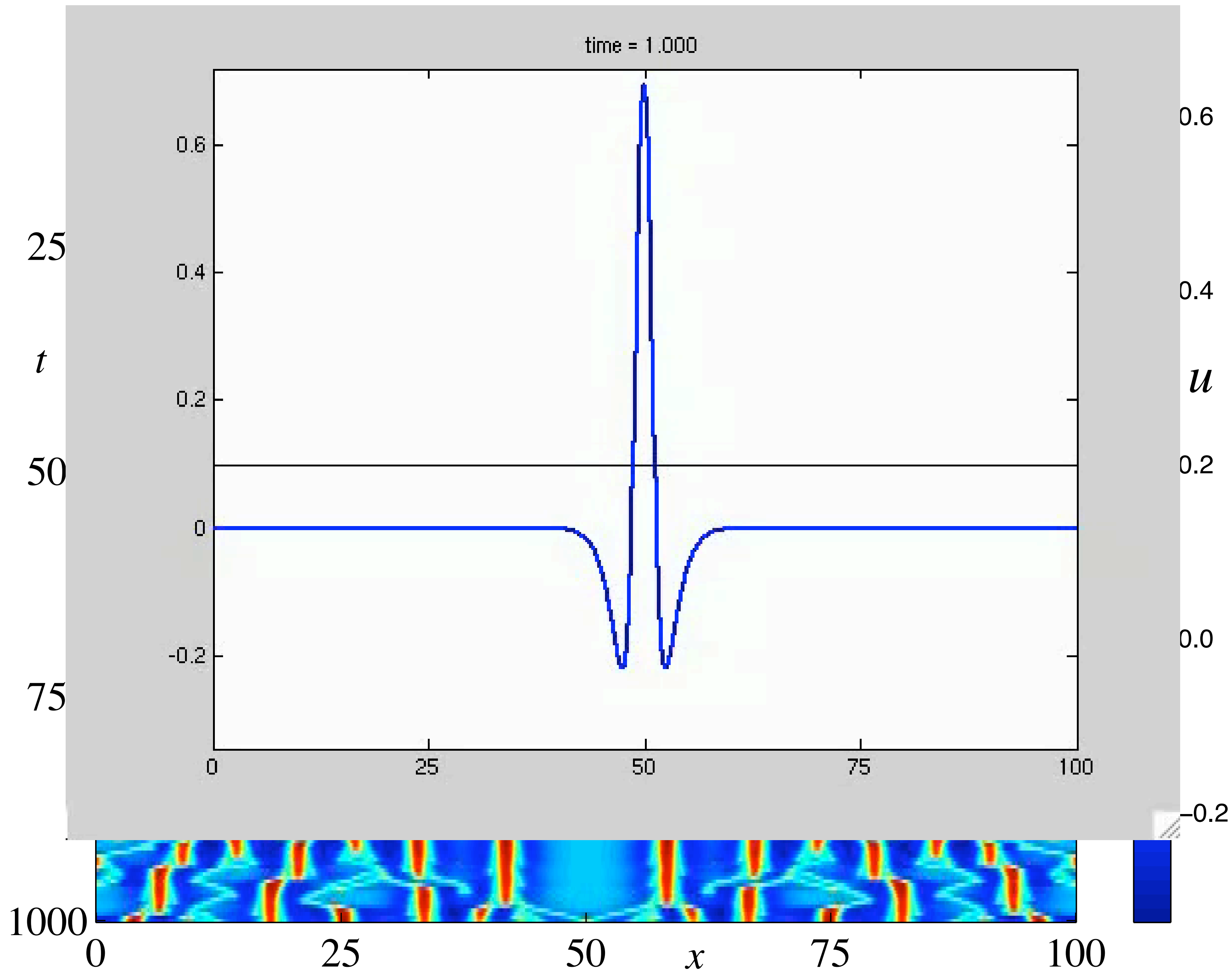

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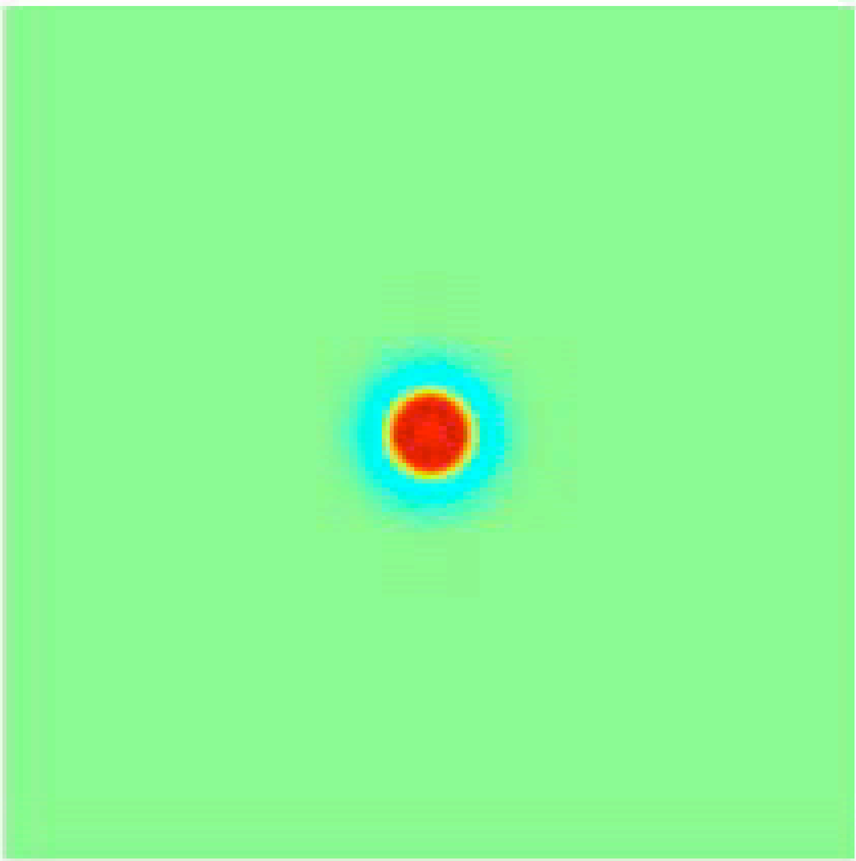
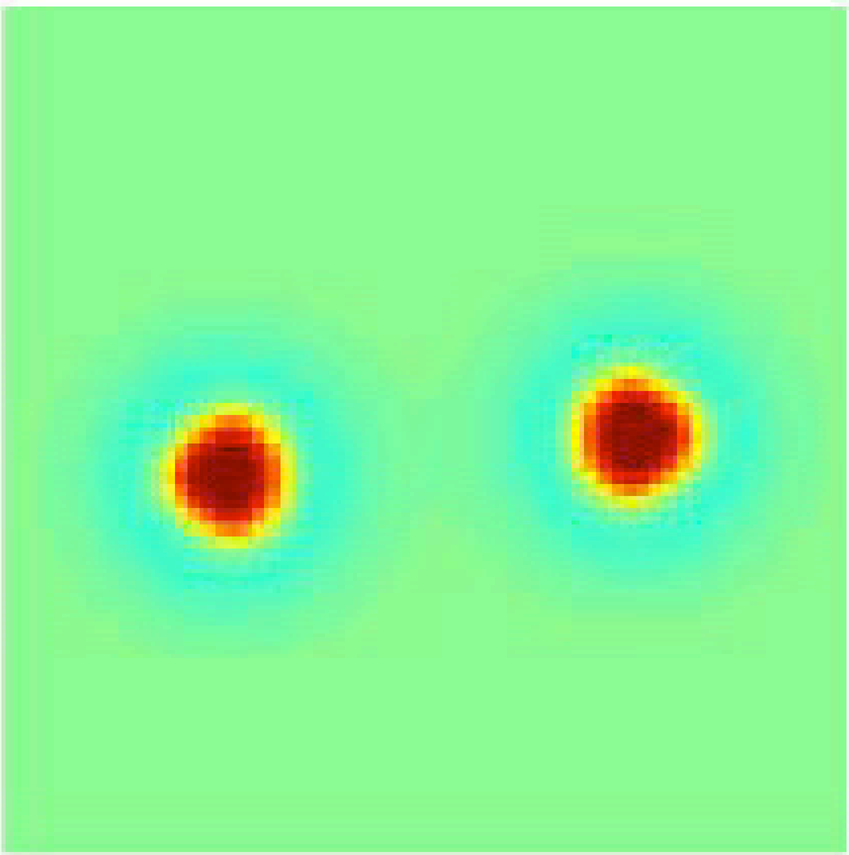
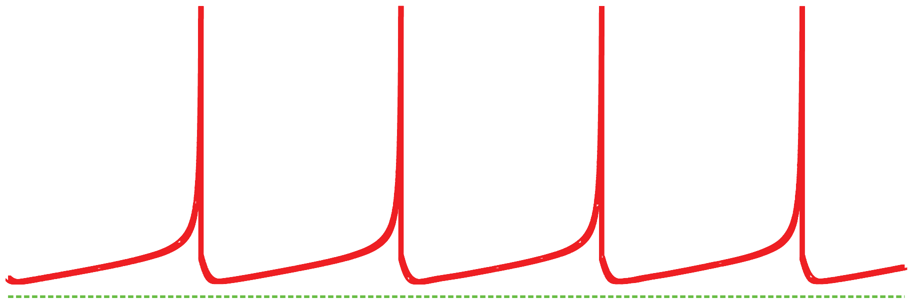
Splitting and scattering



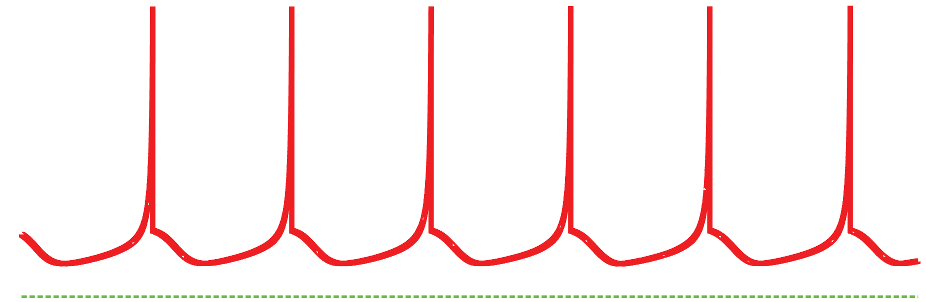


Auto/dispersive solitons as seen in coupled cubic complex Ginzburg-Landau systems and three component reaction-diffusion systems.

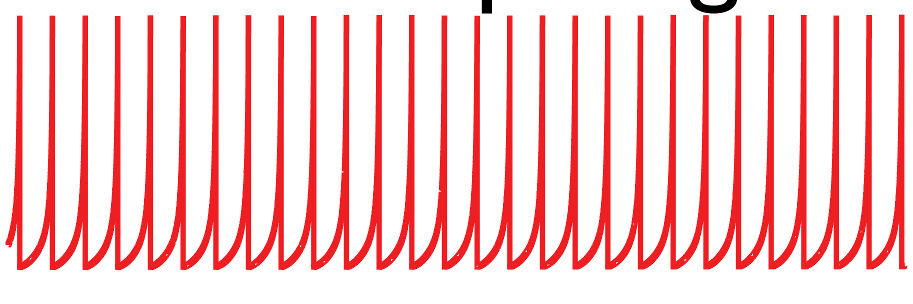
Regular spiking



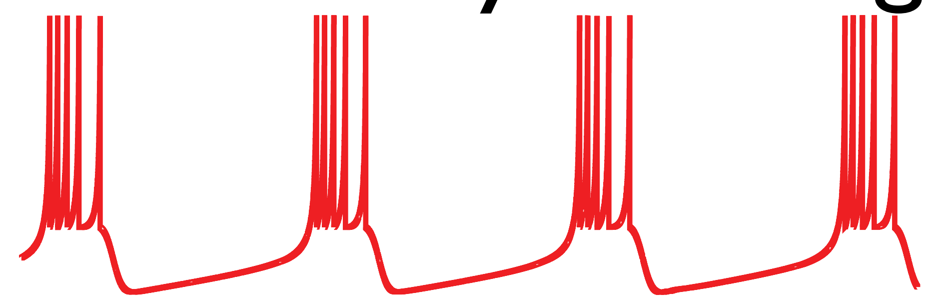
Chattering

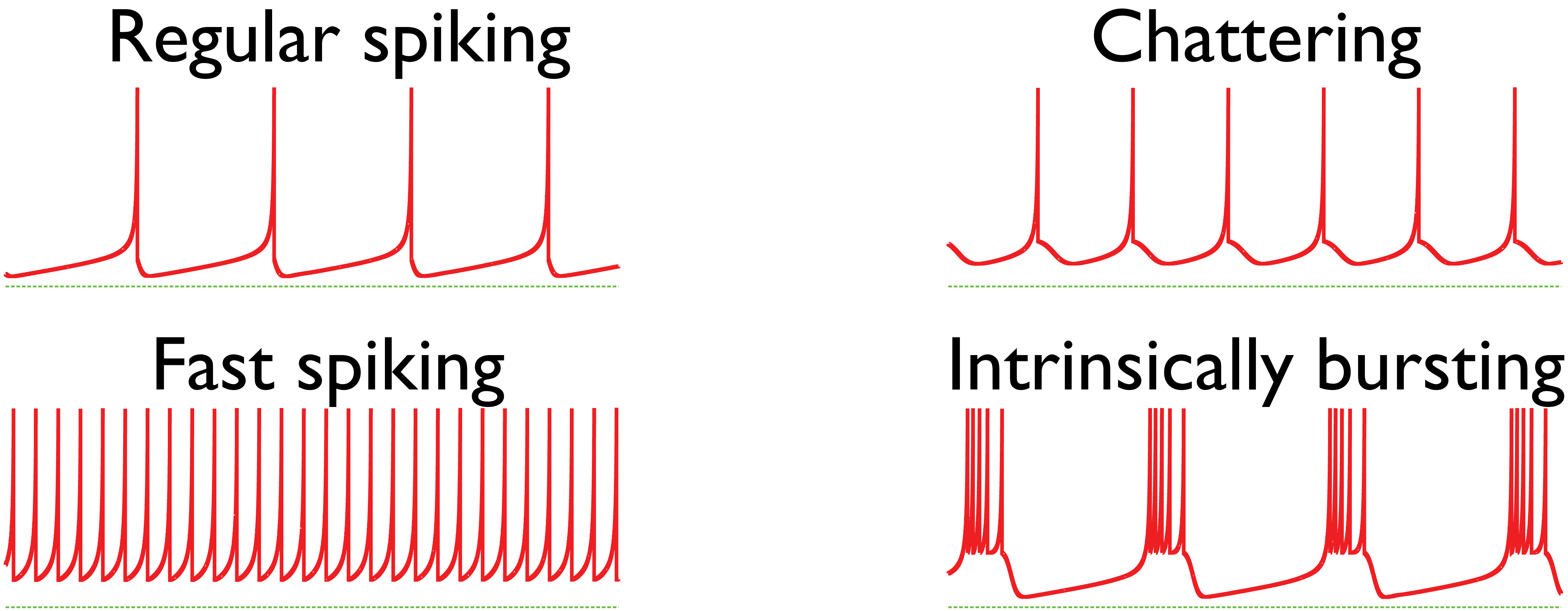


Fast spiking



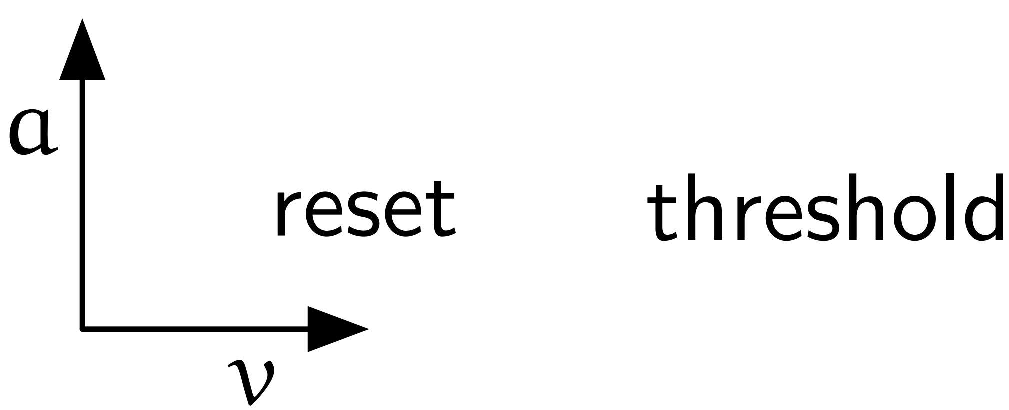
Intrinsically bursting

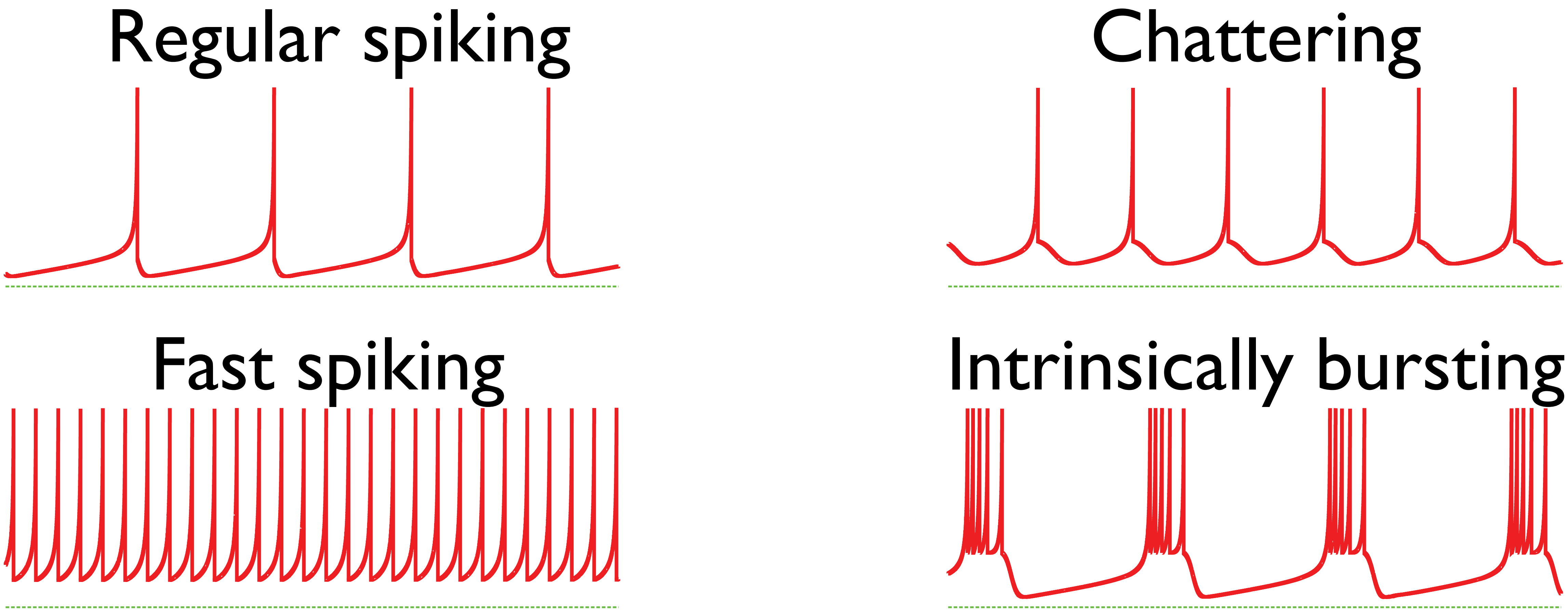


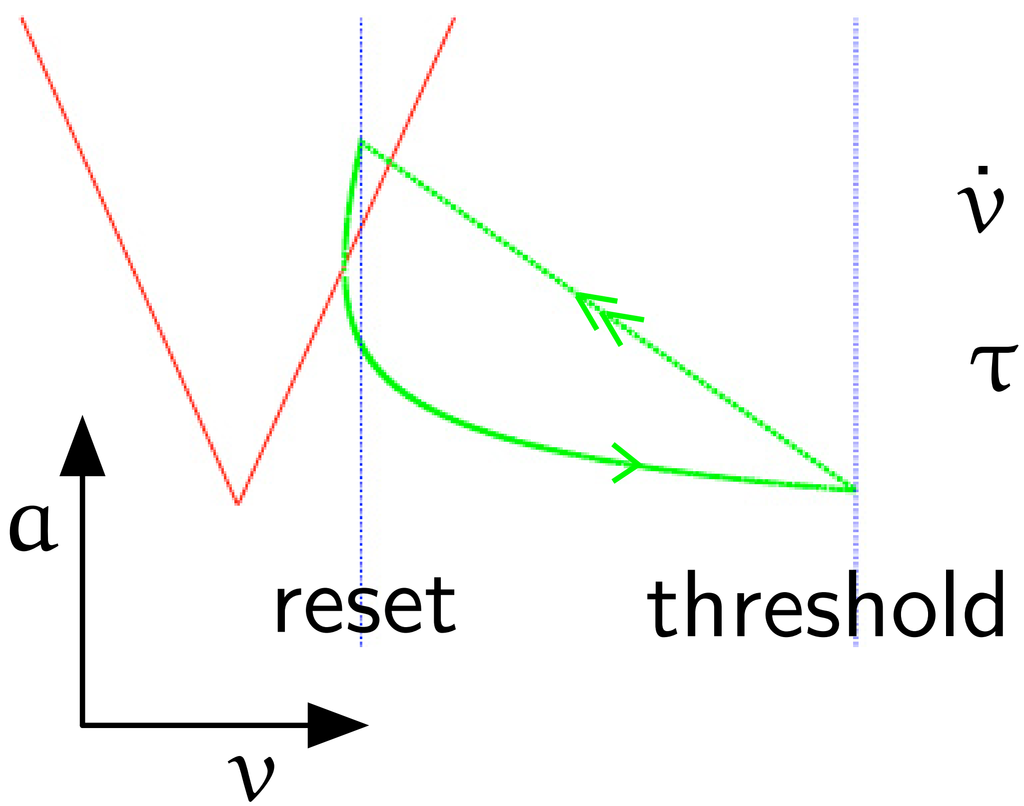


$$\dot{v} = |v| + I - a$$

$$\tau \dot{a} = -a$$



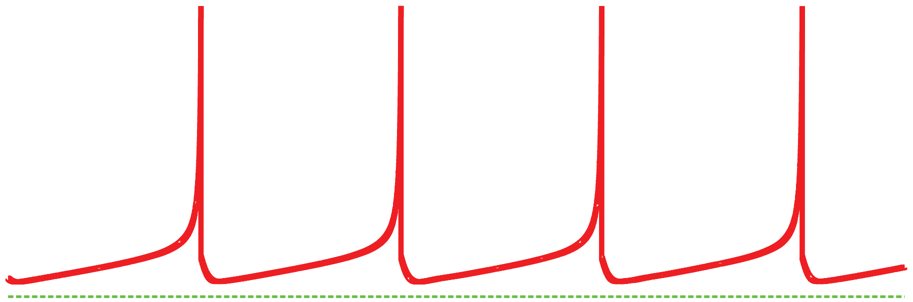




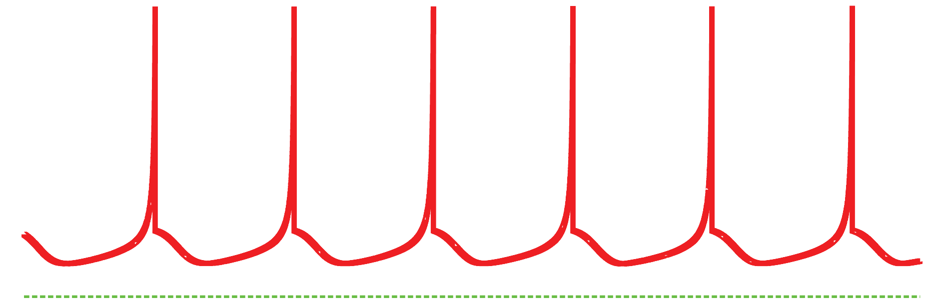
$$\dot{v} = |v| + I - a$$

$$\tau \dot{a} = -a$$

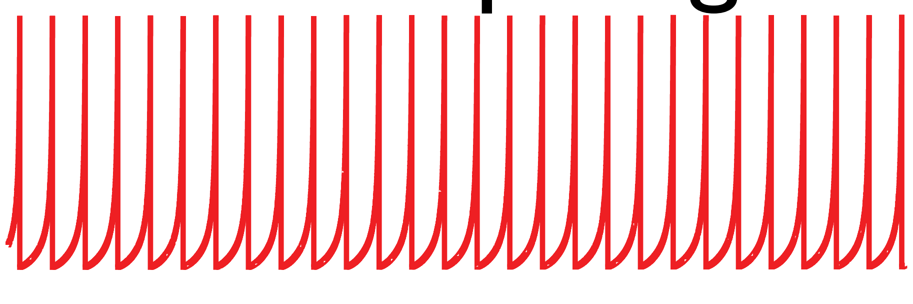
Regular spiking



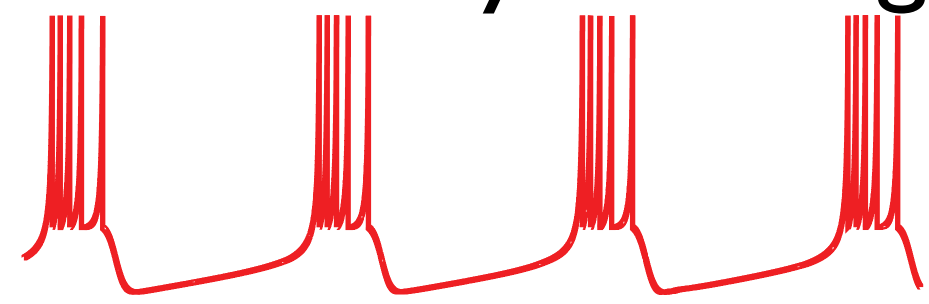
Chattering

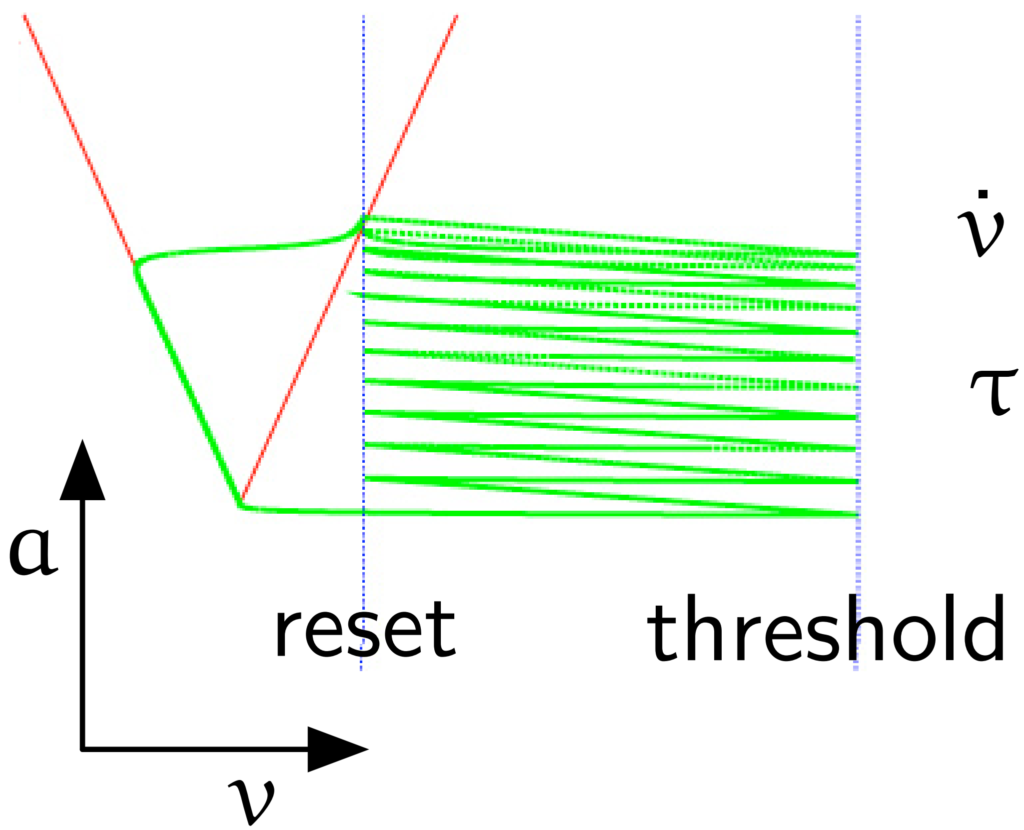


Fast spiking



Intrinsically bursting





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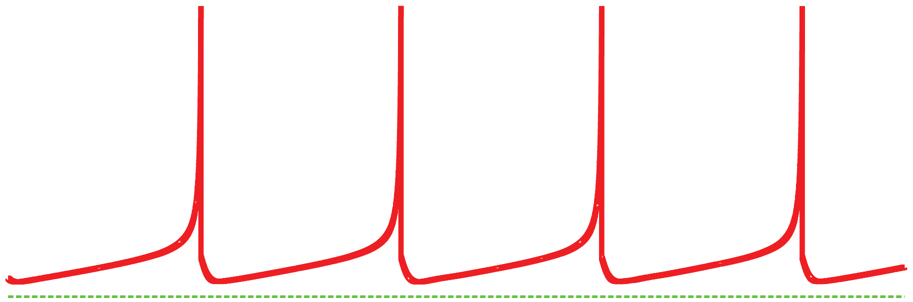
Regular spiking



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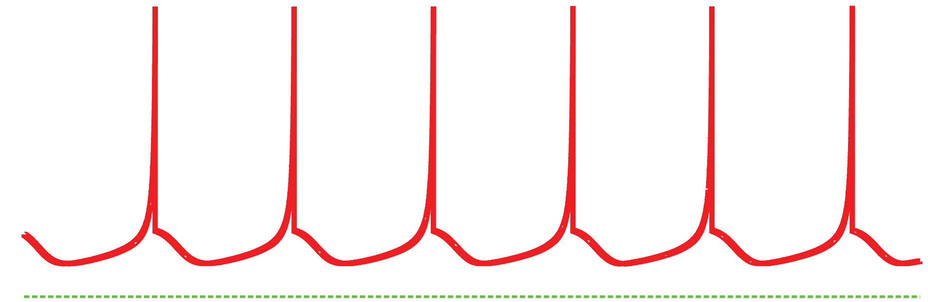

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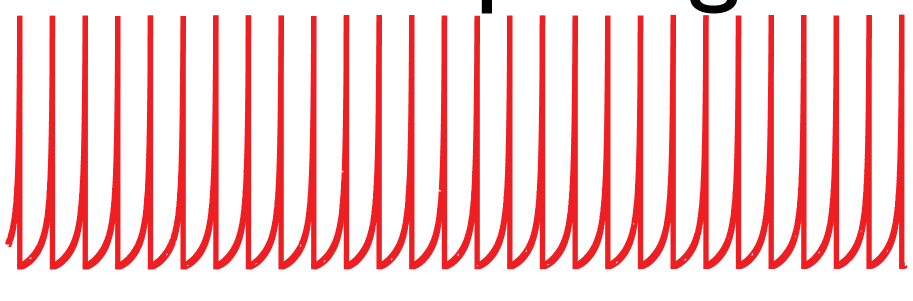
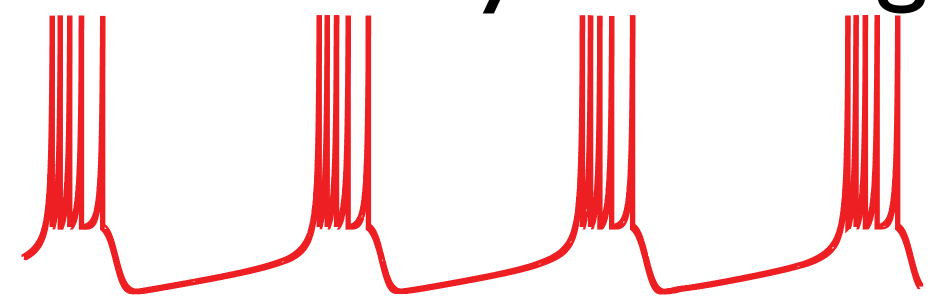
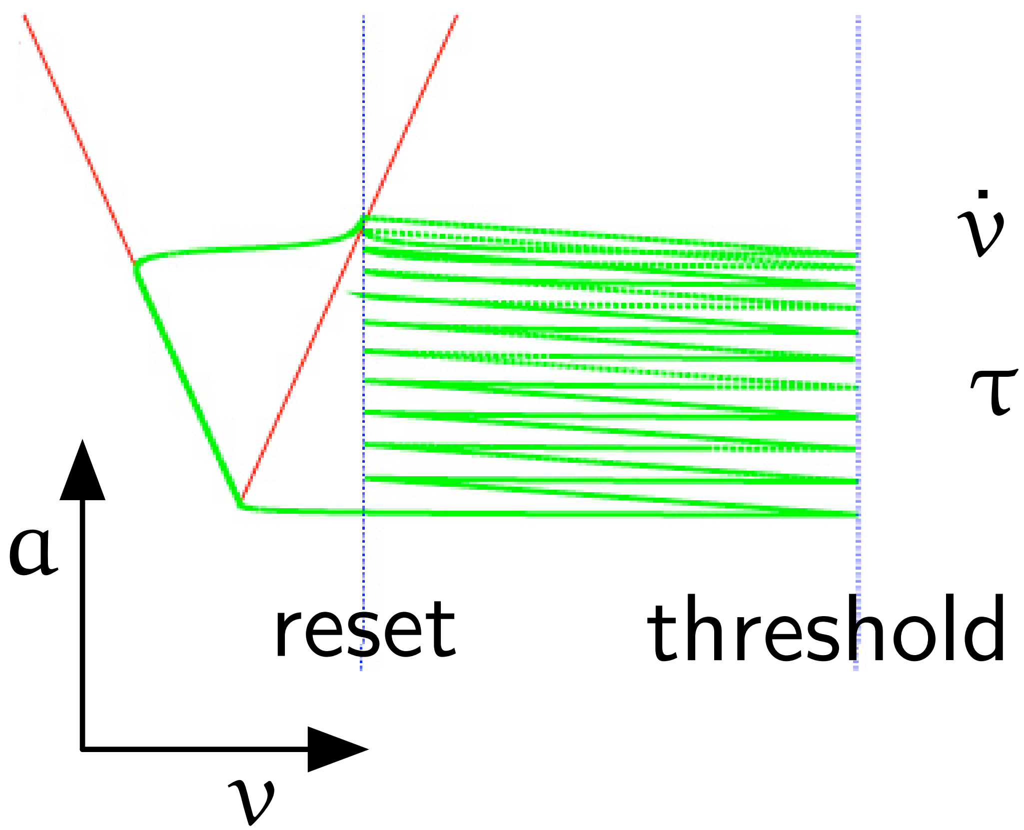


Intrinsically bursting





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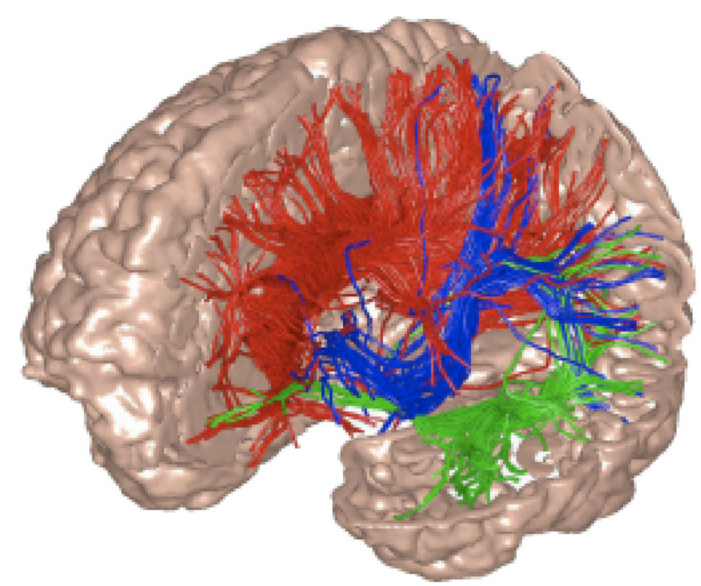
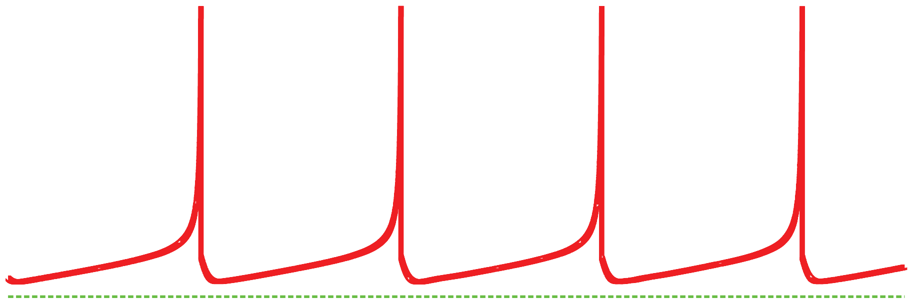
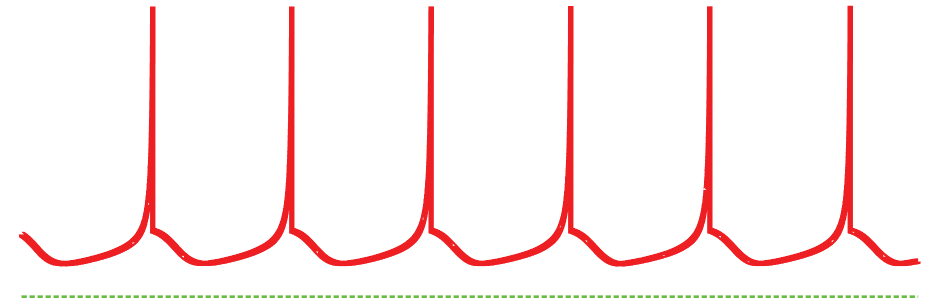


Eugene Izhikevich 2008

Regular spiking



Chattering



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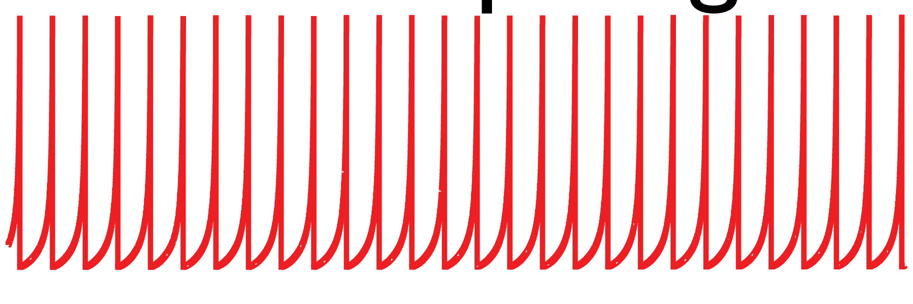
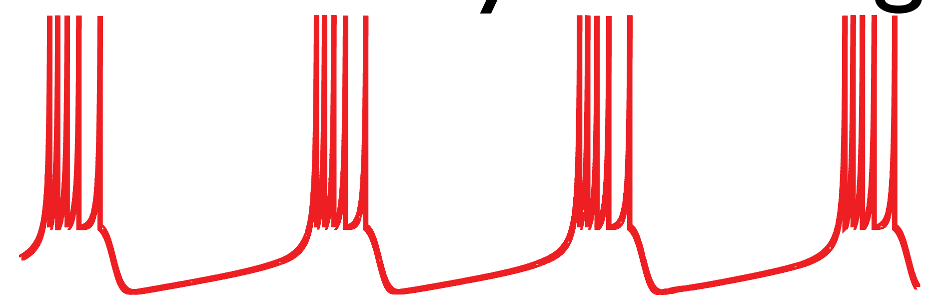
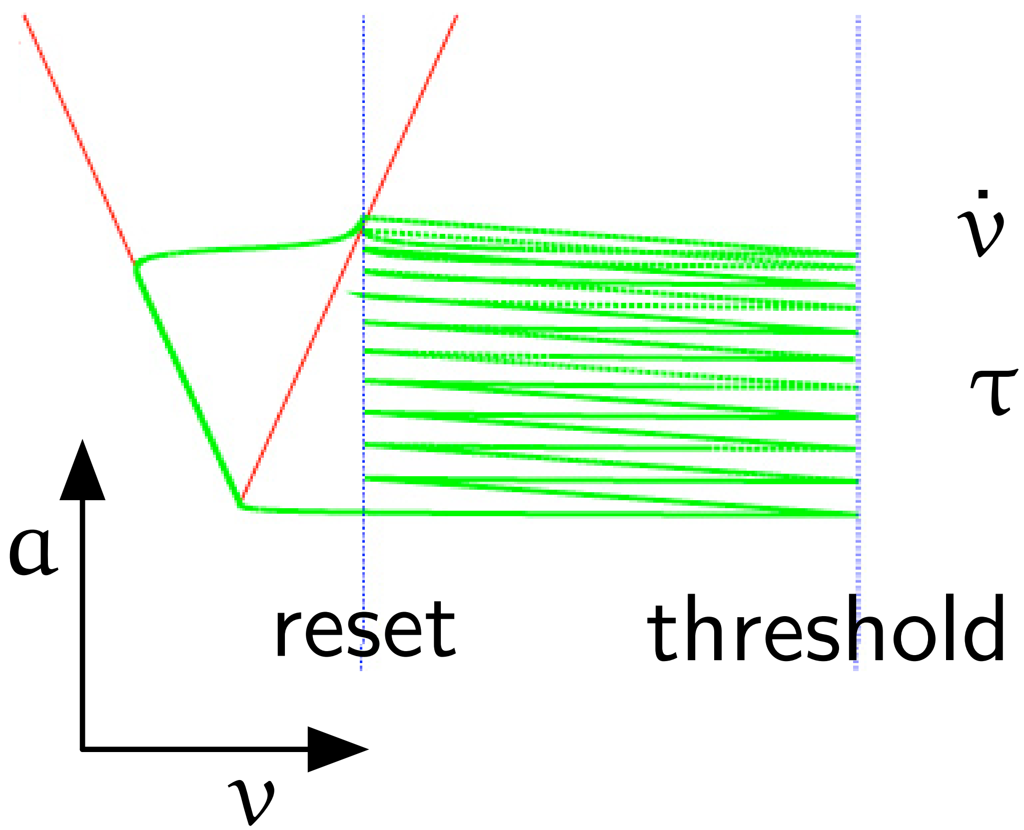


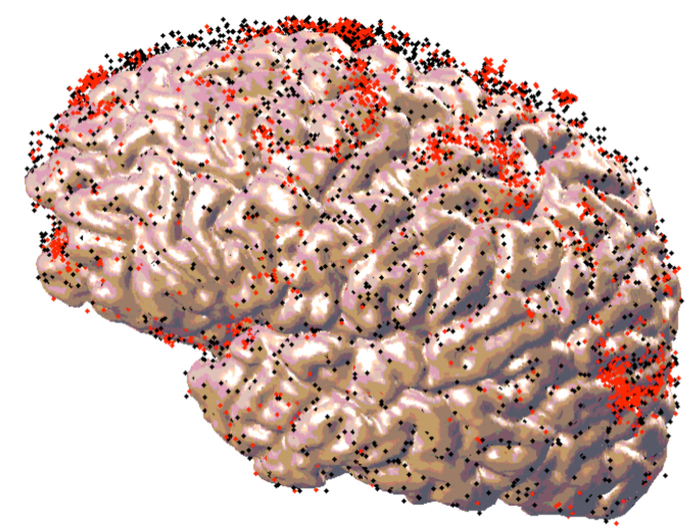
Intrinsically bursting



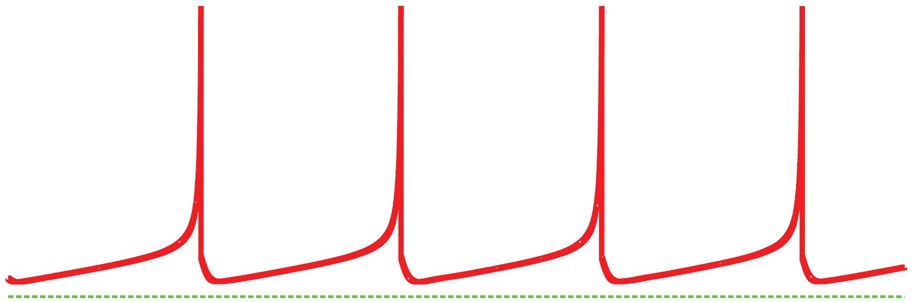


$$\dot{v} = |v| +$$

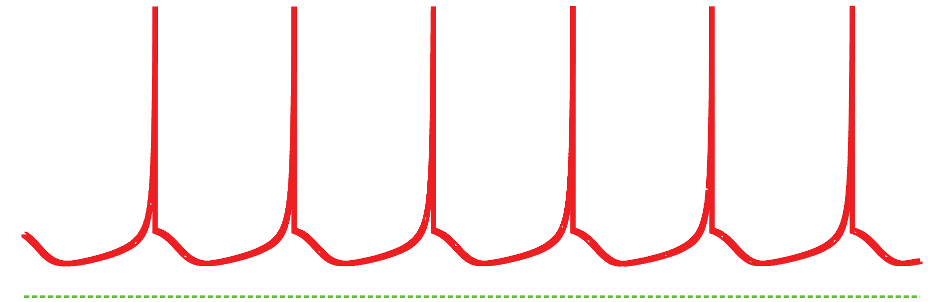
$$\tau \dot{a} = -a$$



Regular spiking



Chattering



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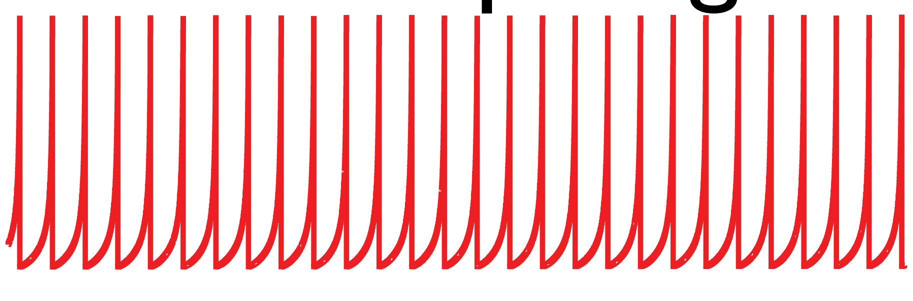

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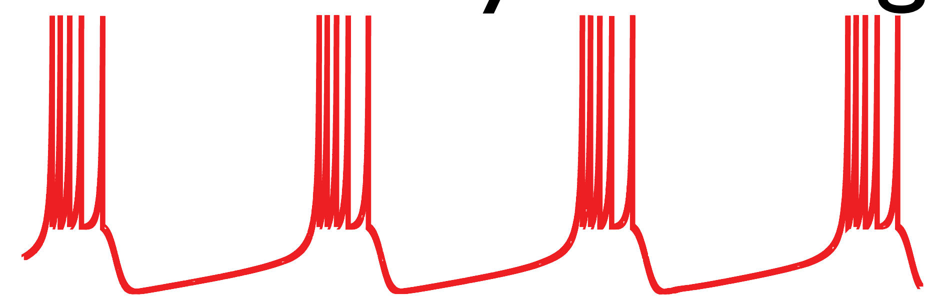

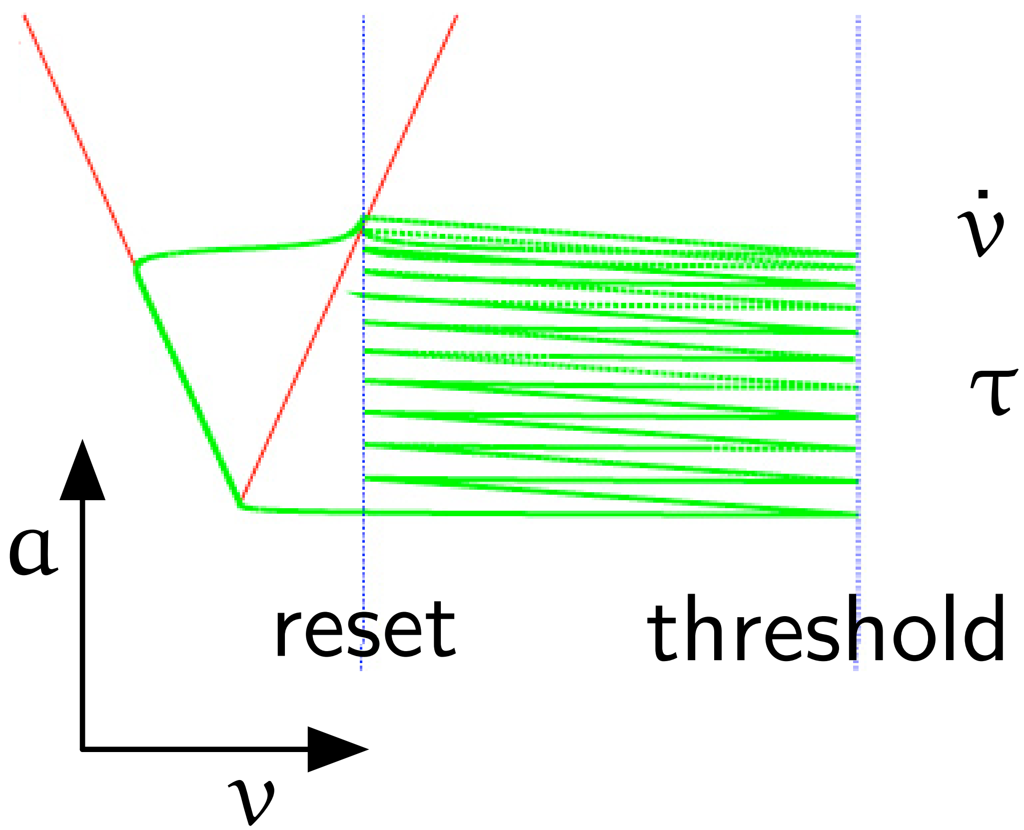

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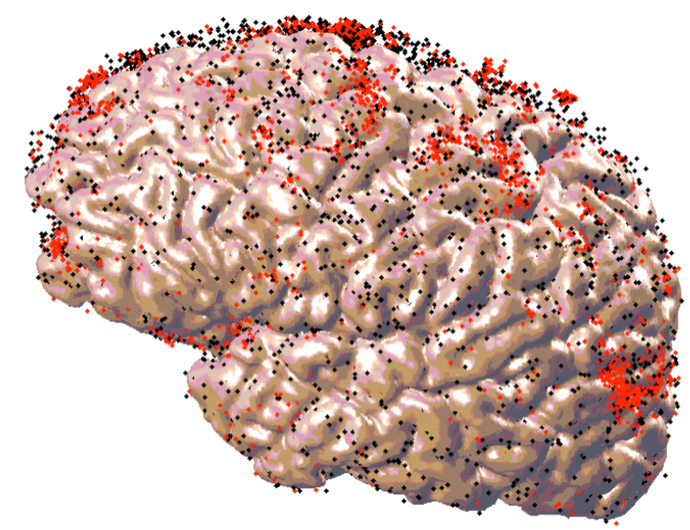
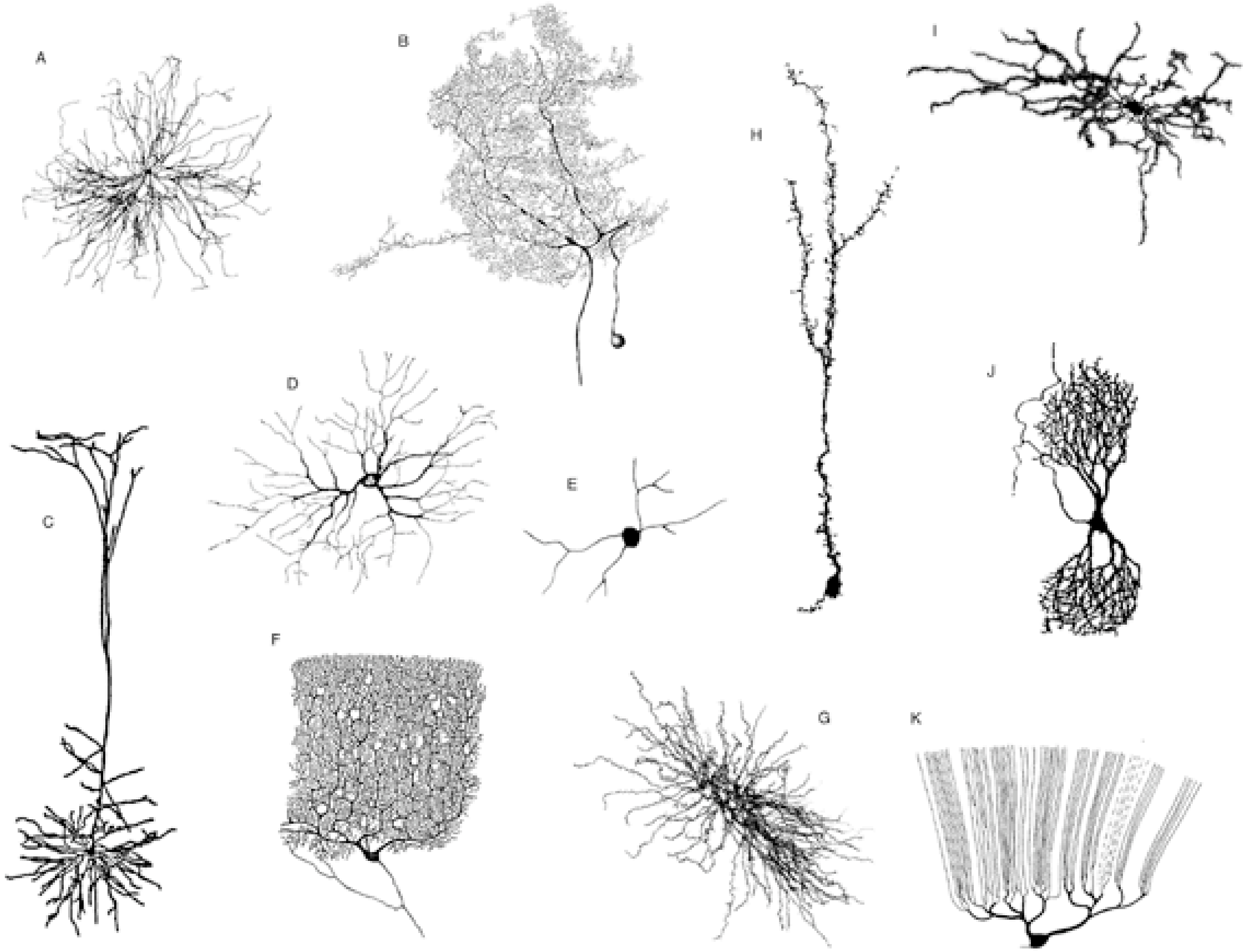
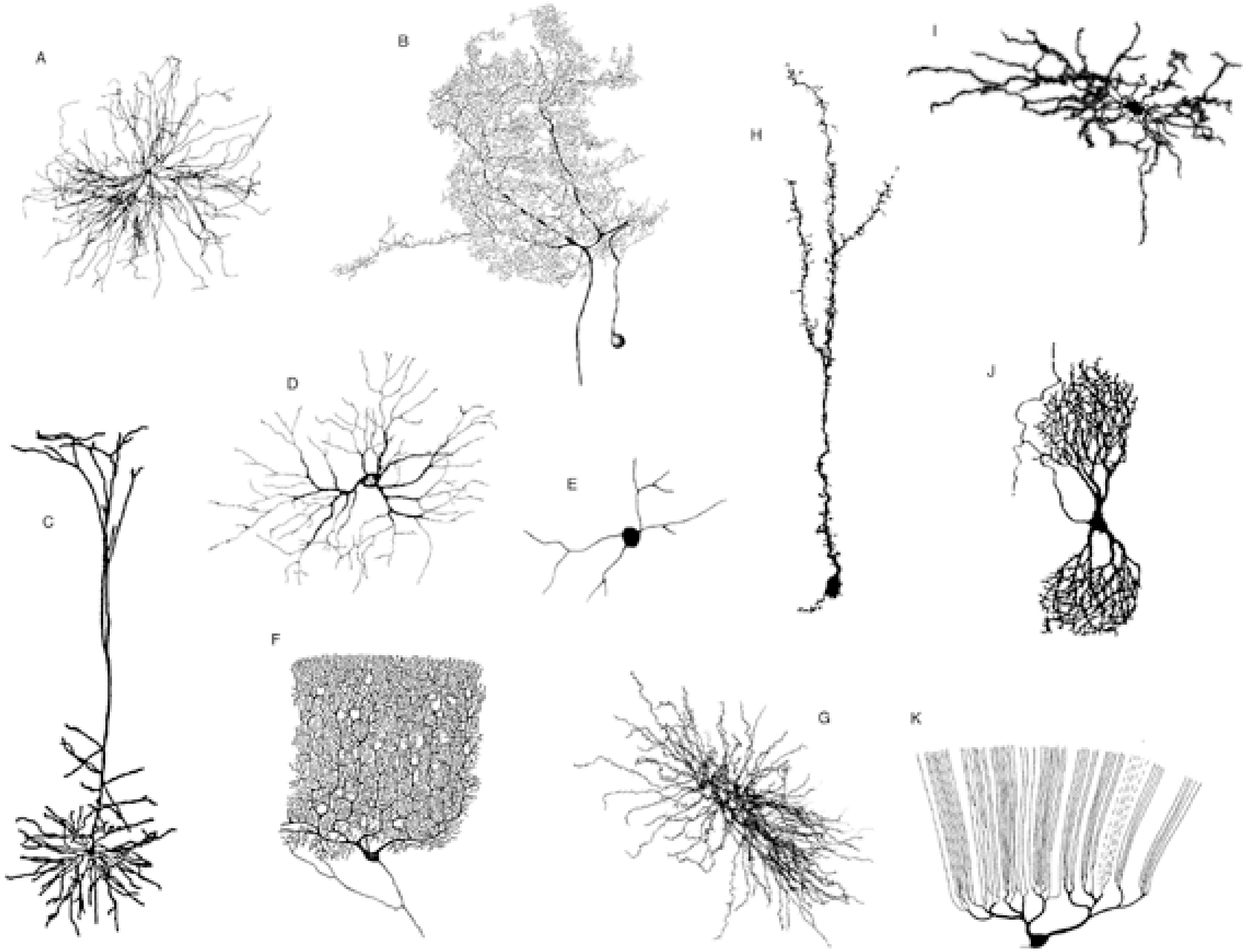


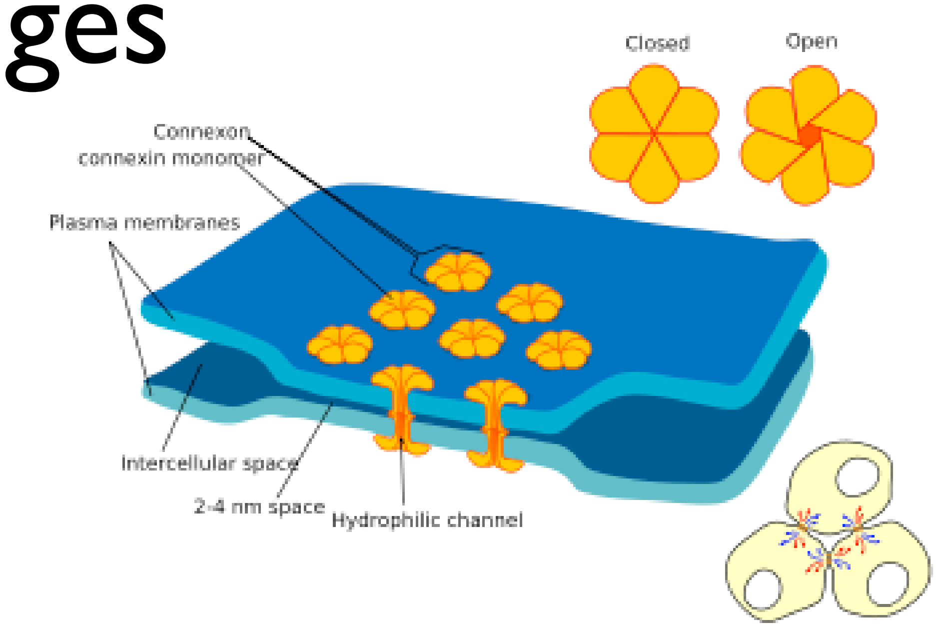
S Coombes and M Zachariou 2009, in Coherent Behavior in Neuronal Networks (Ed. Rubin, Josic, Matias, Romo), Springer.

Further Challenges

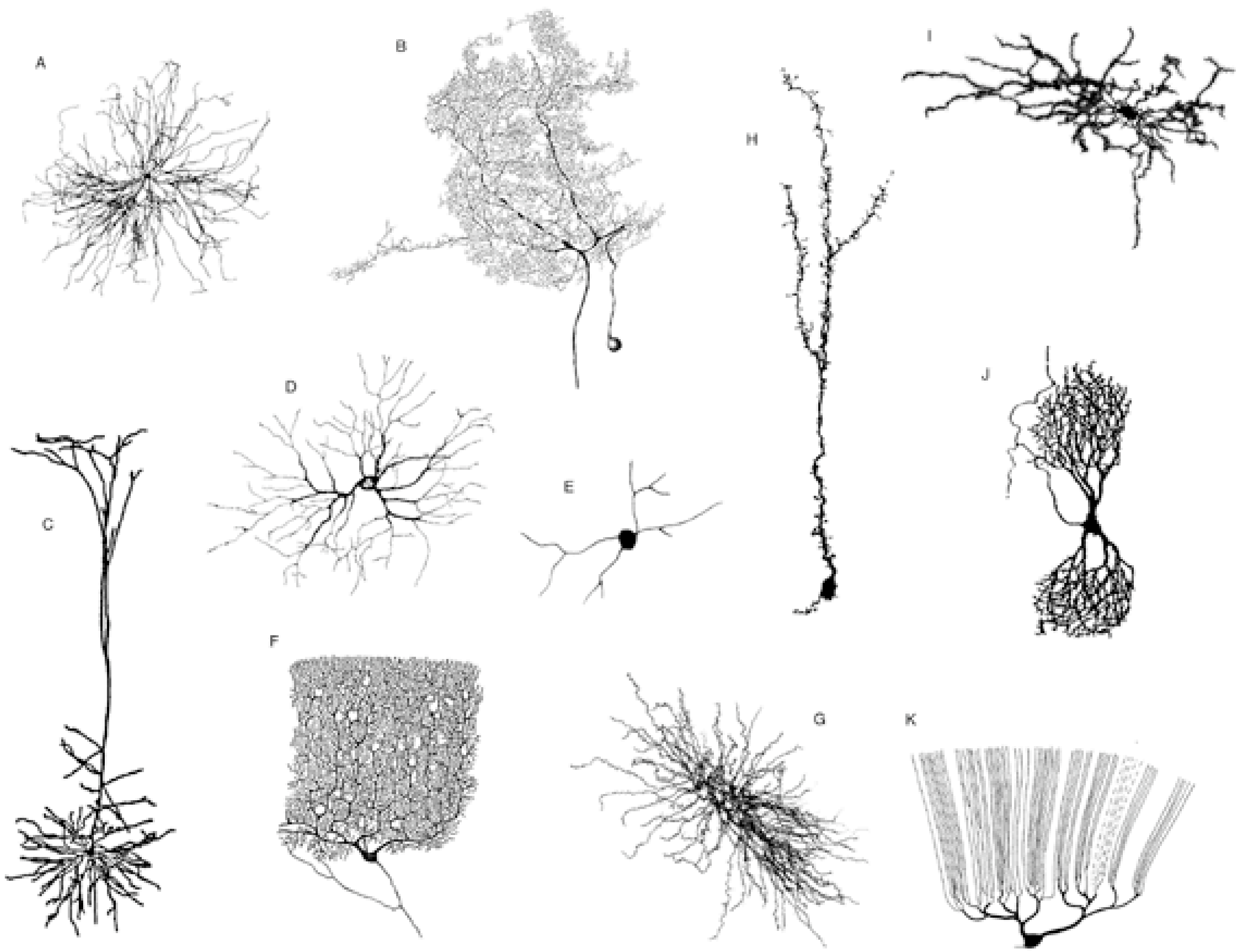


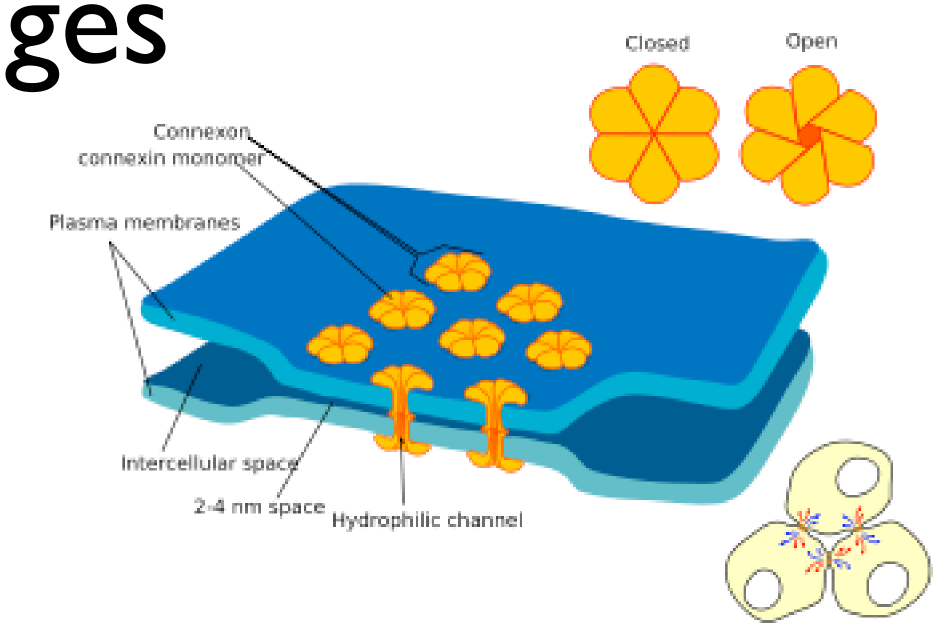
Further Challenges

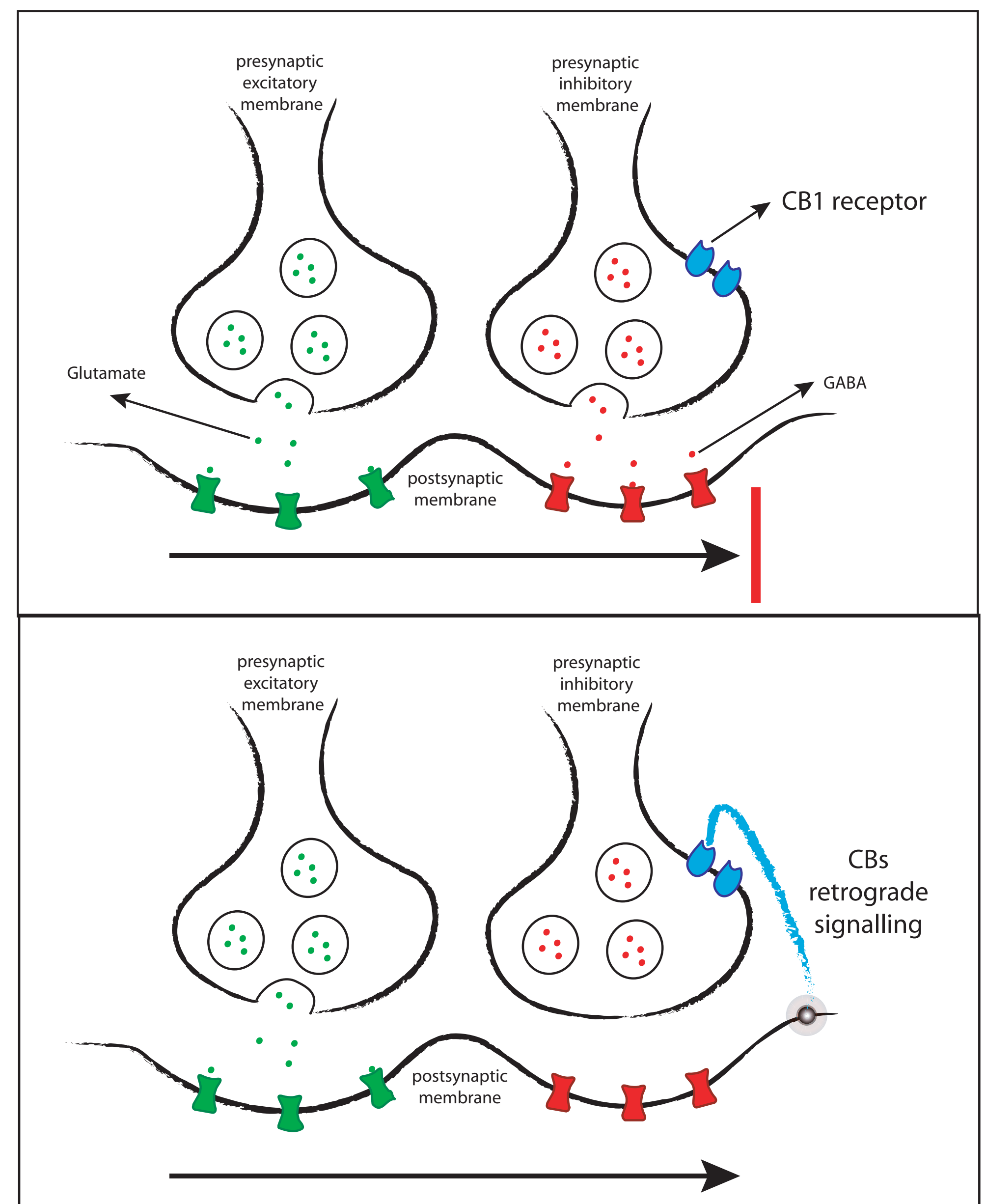




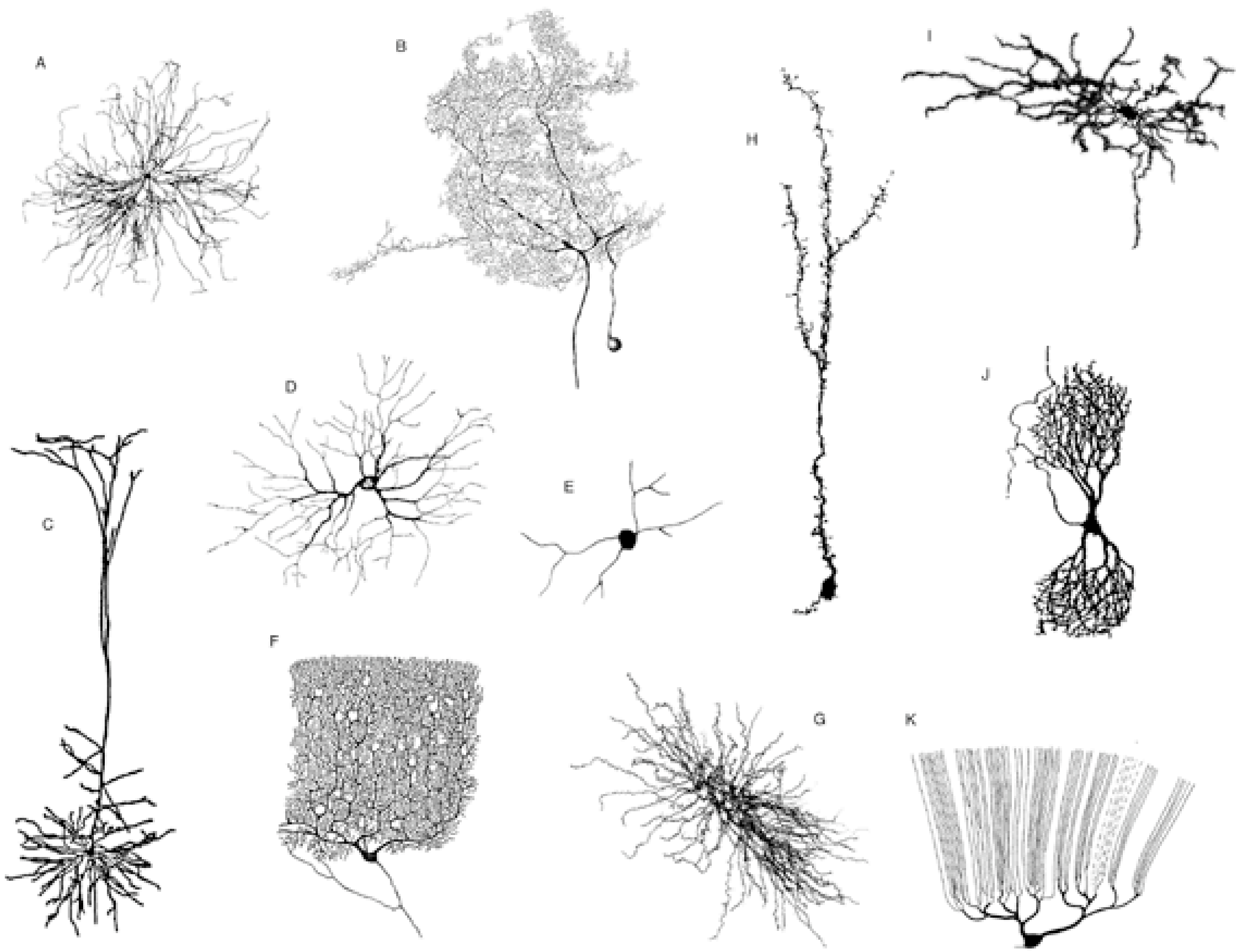
Further Challenges

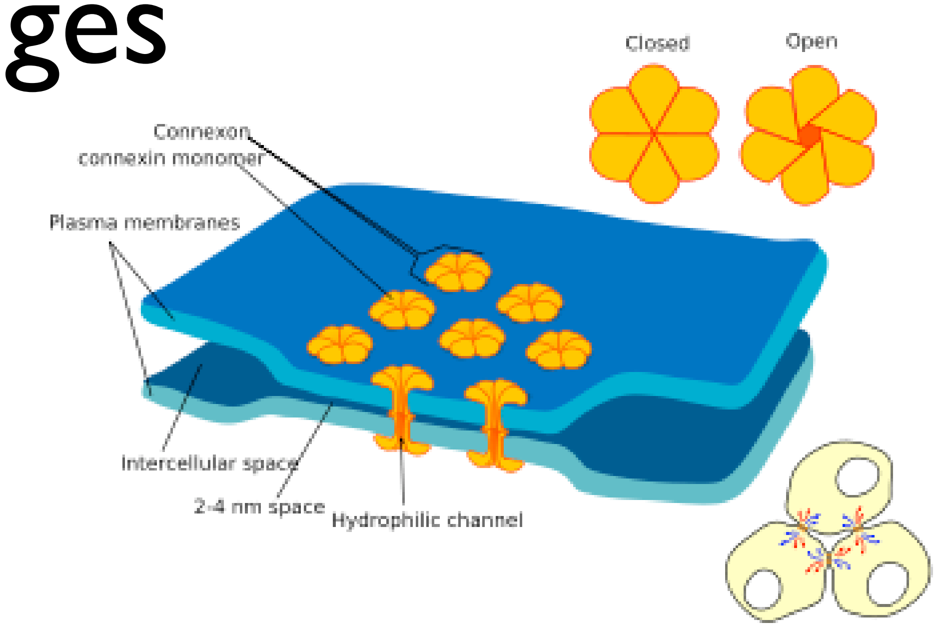


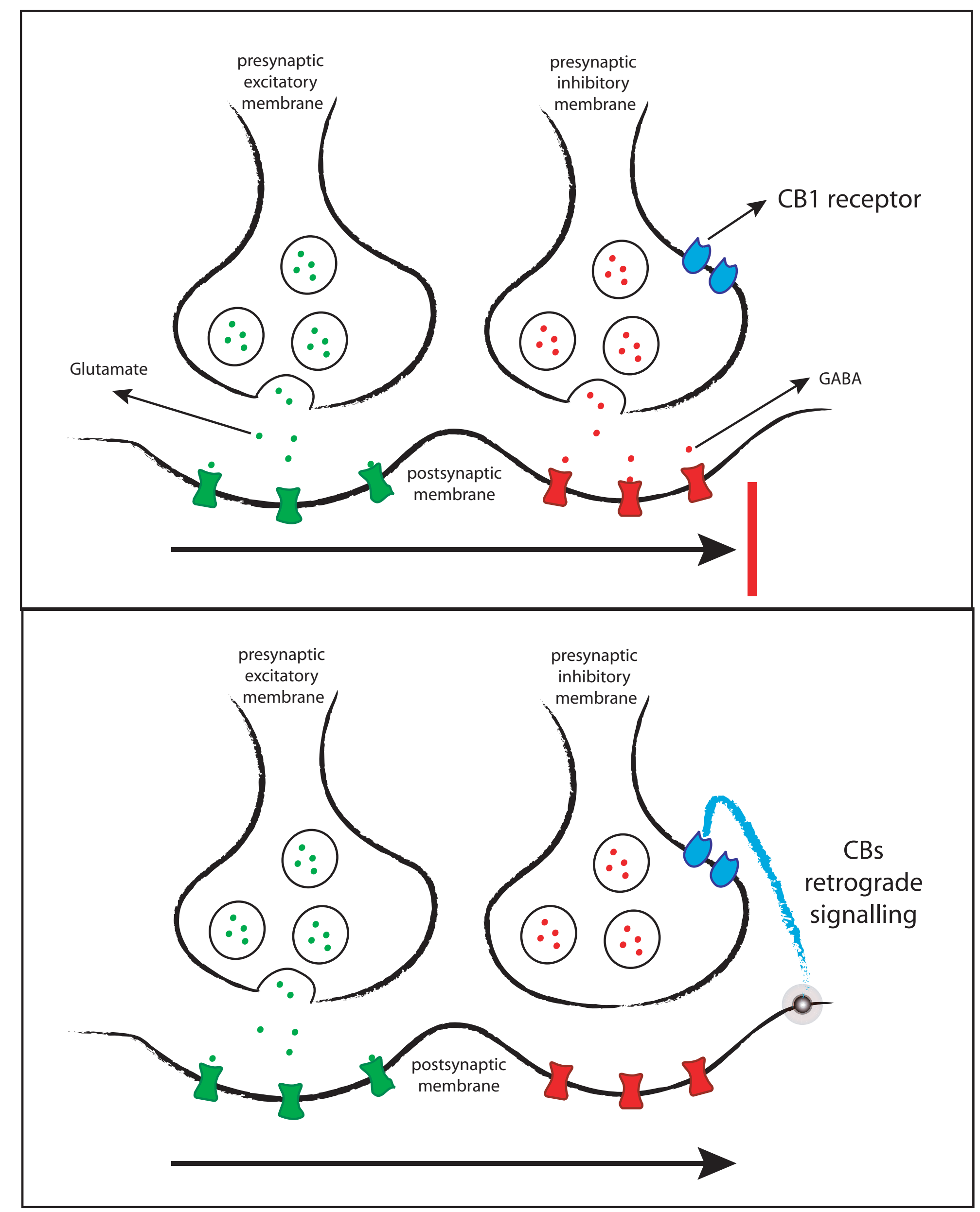


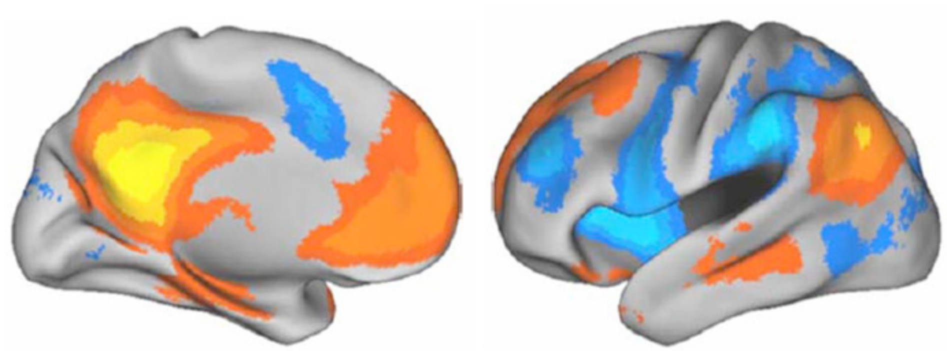


Further Challenges









Default mode network and ultra slow coherent oscillations

In collaboration with

Nikola Venkov
(Notts)

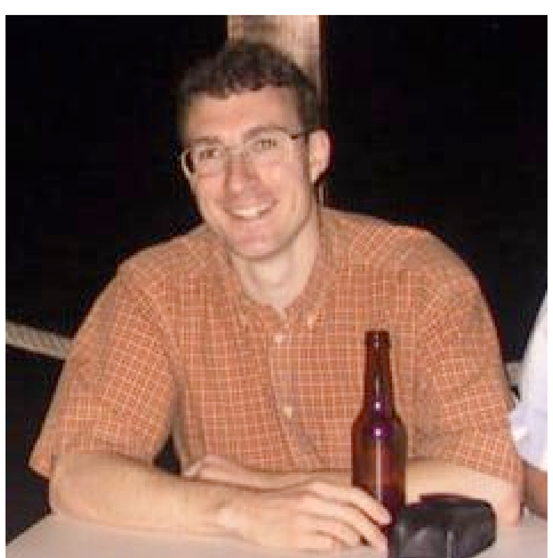
Gabriel Lord
(Heriot-Watt)

Yulia Timofeeva
(Warwick)

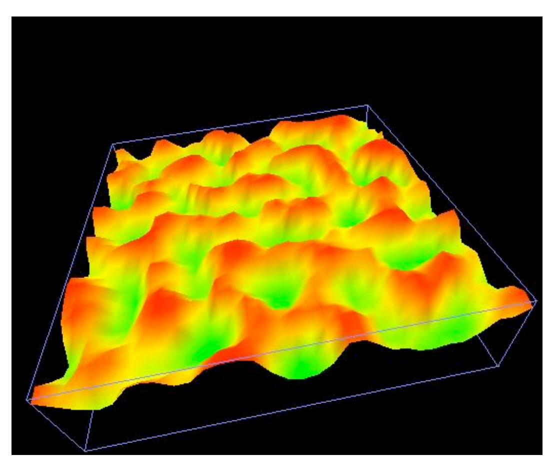
David Liley
(Melbourne)

EPSRC Engineering and Physical Sciences Research Council

Markus Owen (Notts)



Ingo Bojak (Nijmegen)



Carlo Laing (Massey, NZ)