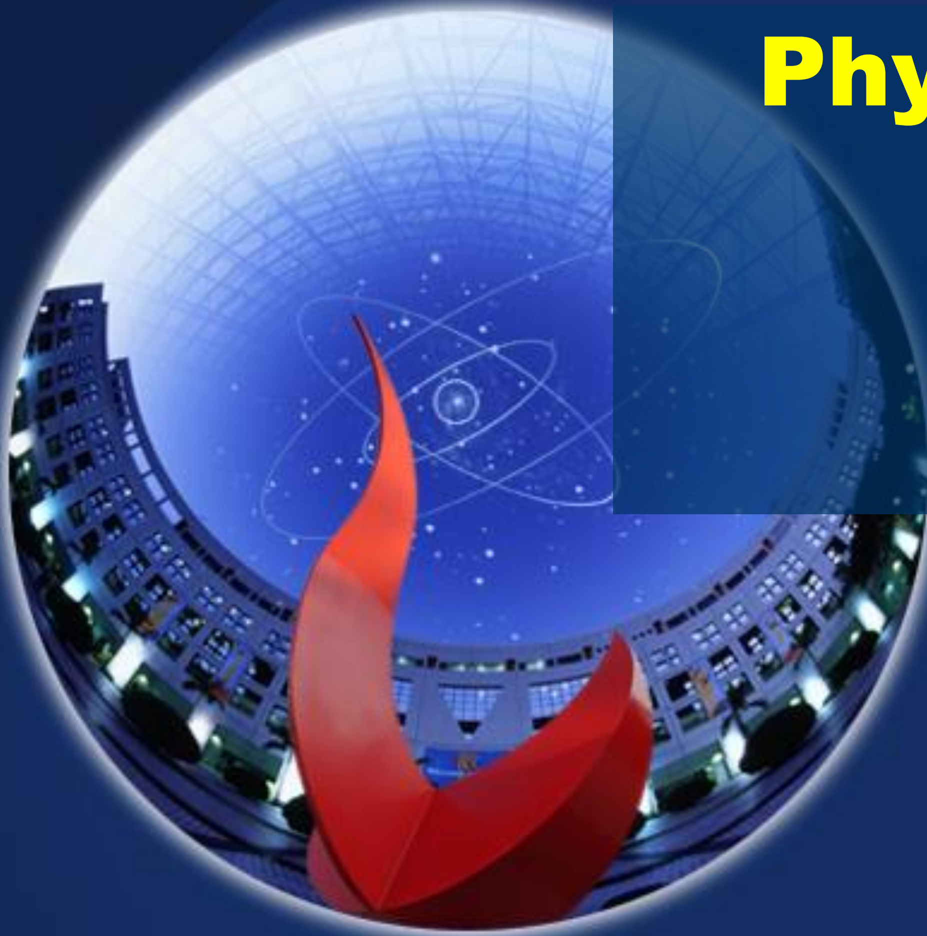
IAS 2015



Physical Principles in Dynamical Information Processing

K. Y. Michael Wong

Hong Kong University of Science and Technology

香港科技大學
HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Acknowledgement

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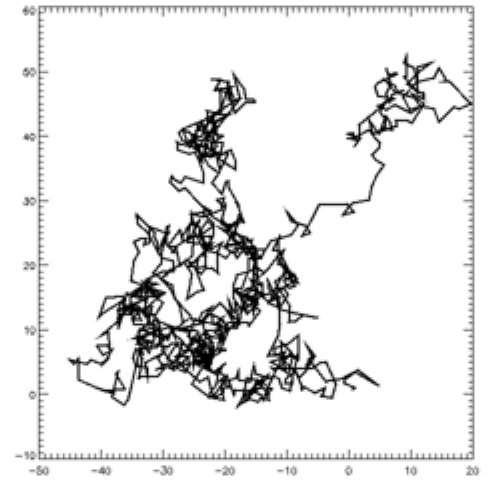
A Bridge to AI

What are the principles common to both biological and artificial information processors?

Clarkia Pulchella (Pink Fairies)

Brownian Motion

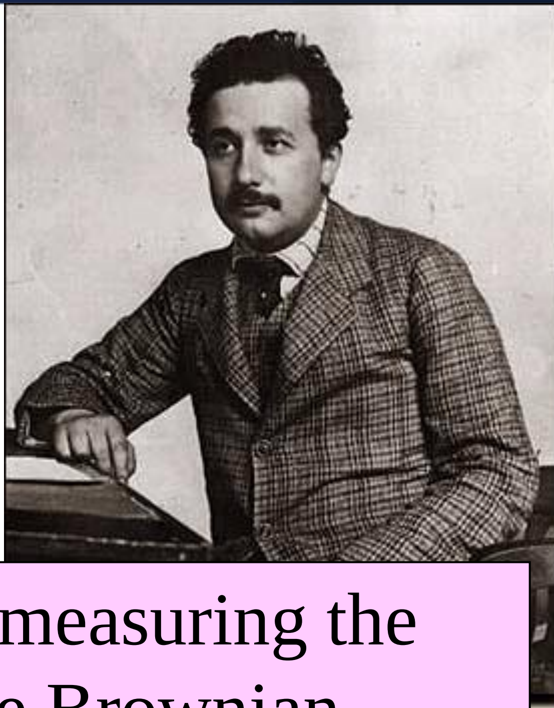


- In 1827, Brown studied the fertilization process in *Clarkia pulchella*.
- He noticed a "rapid oscillatory motion" of the pollen grains suspended in water under the microscope.
- Initially, he believed that such activity was peculiar to the male sexual cells of plants.
- Pollen of plants dead for over a century showed the same movement.
- The same motion could be observed even with chips of glass or granite or particles of smoke.

Einstein 1905

- The analysis of Brownian motion was done by Einstein in 1905.
- Einstein relation:

$$D = \frac{k_B T}{6\pi\eta a}$$



D = diffusion coefficient, measuring the fluctuation of the Brownian particles at equilibrium

η = viscosity, measuring the response of the Brownian particles to an external driving force

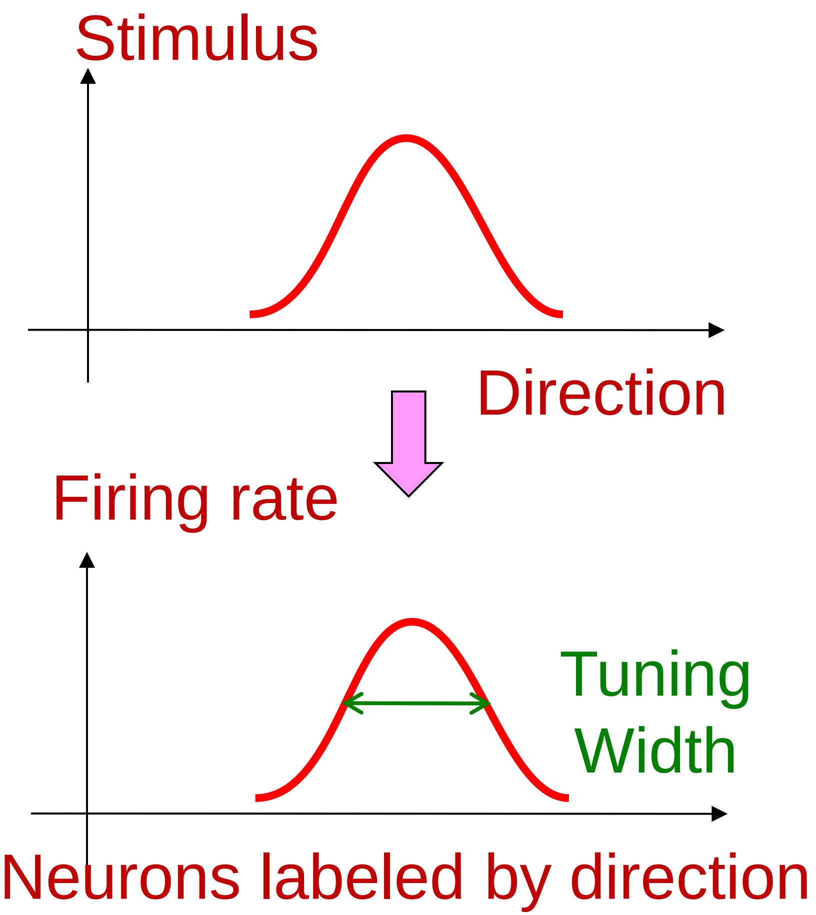
Fluctuation-response relations

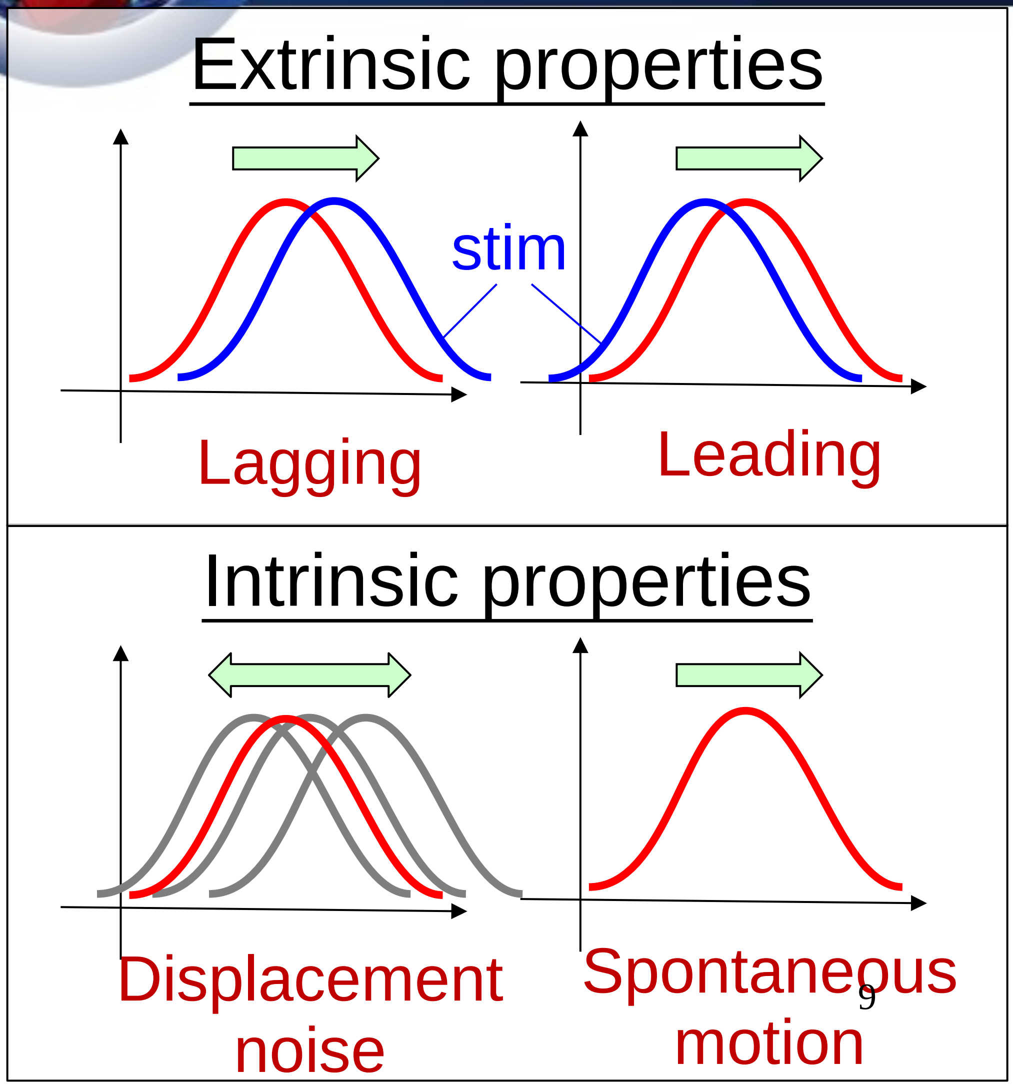
System	Fluctuation (Intrinsic Behavior)	Response (Extrinsic Behavior)
Brownian particles	Mean square displacement	Diffusion
Electrons	Nyquist noise	Conductance
Solids	Fluctuation of Energy	Heat Capacity

How About Neural Systems?

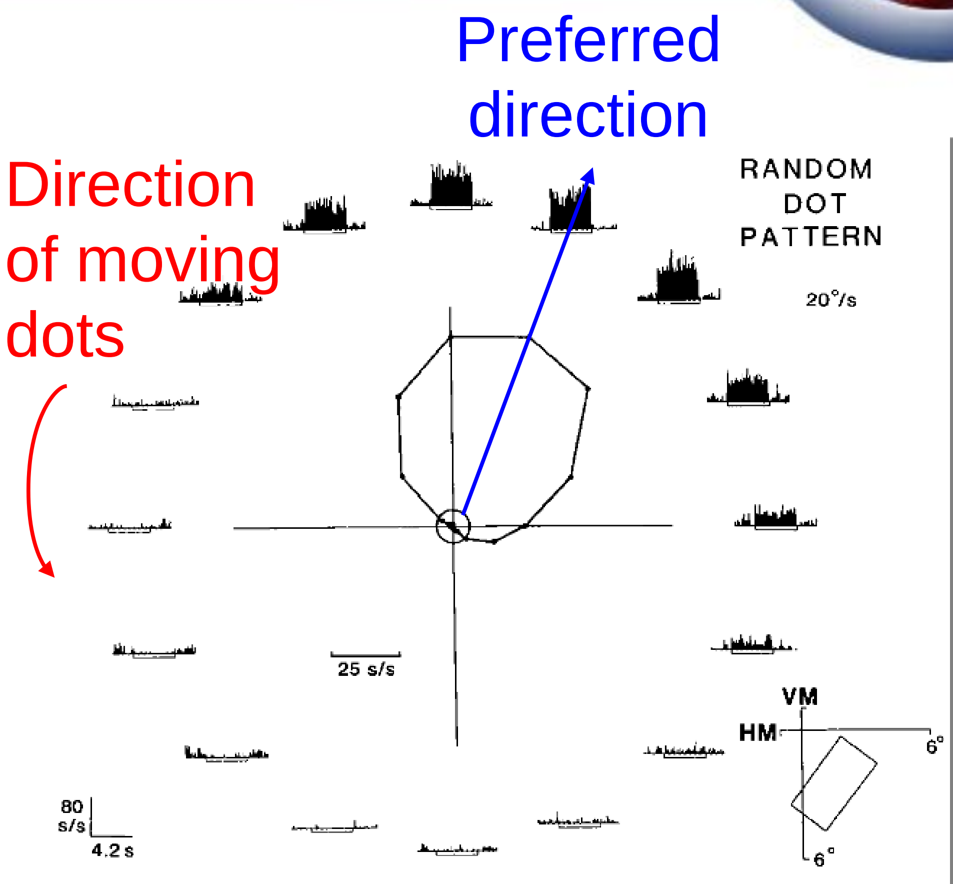
- How are the intrinsic (without stimuli) and extrinsic (with stimuli) properties related?
- What are the implications (esp. to neural responses)?
- Especially in the processing of continuous information, e.g. orientation, head-direction, spatial location

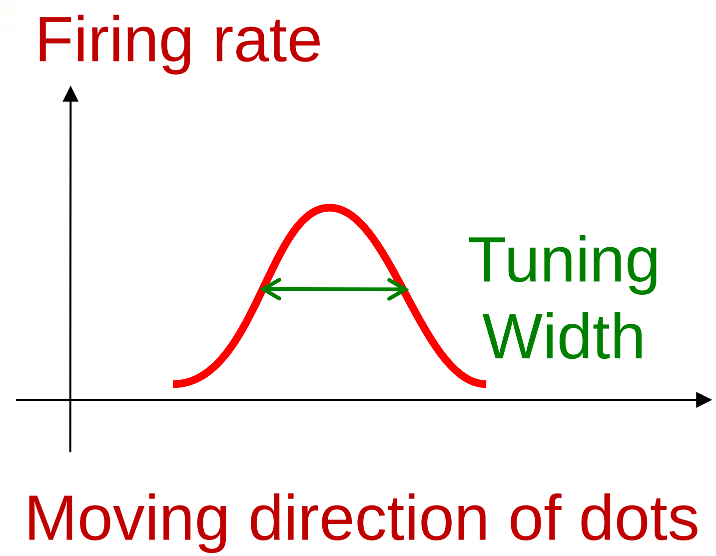
Processing Continuous Information





Continuous Info in Monkeys



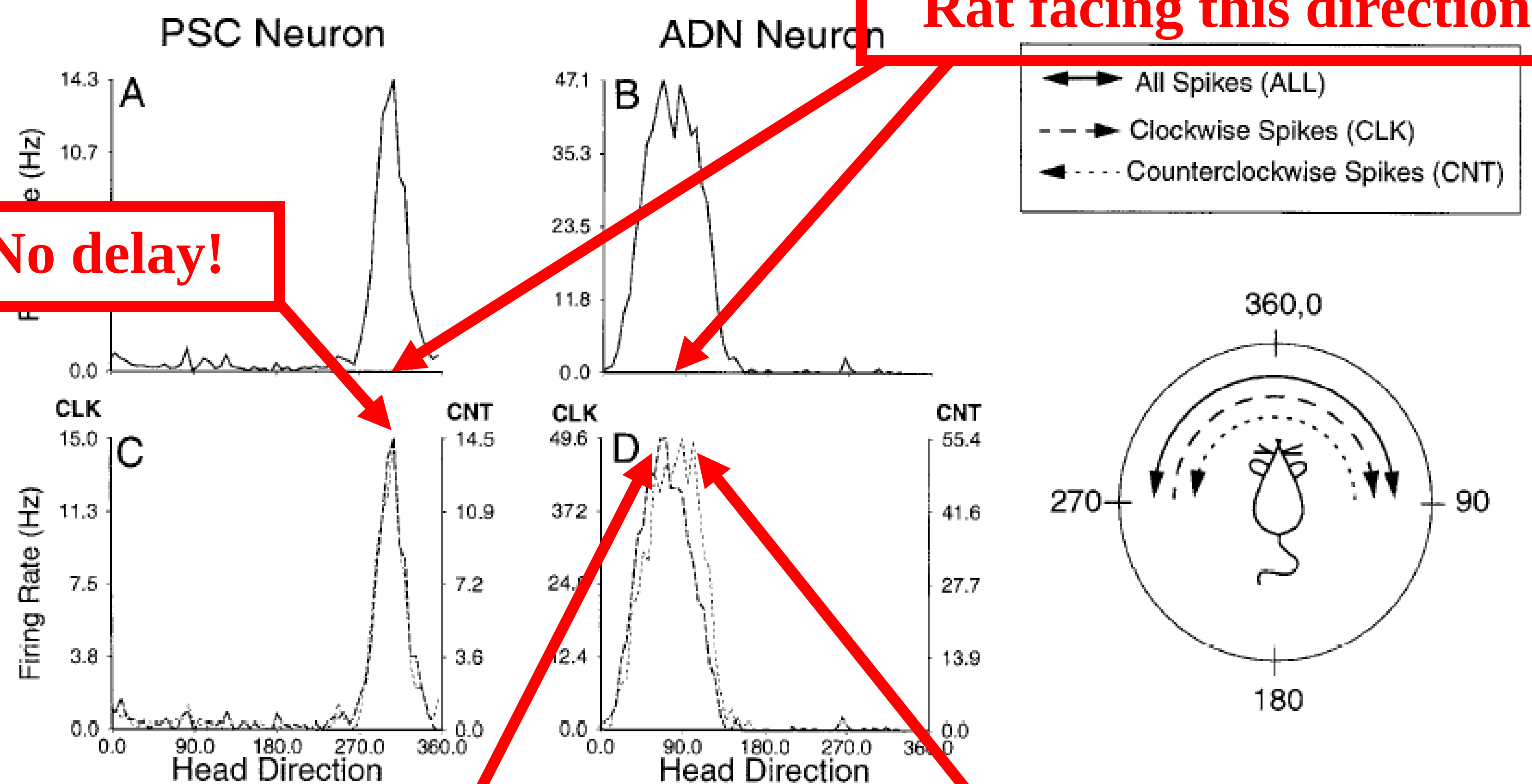


Activities of macaque Middle Temporal (MT) neurons (TD Albright 1984)

HD Cells Predict

Rat facing this direction

No delay!



Turning clockwise: earlier!

Turning anticlockwise: earlier!

Blair and Sharp, J. Neurosci. (1995)

Time Delays are Pervasive

- Why is prediction useful?
- Processing and transmission delays in neural systems: 50 to 100 ms
- Federer's fastest serve speed: 135 mph
- In 100 ms, displacement = 6 m!

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Life-and-Death Issue

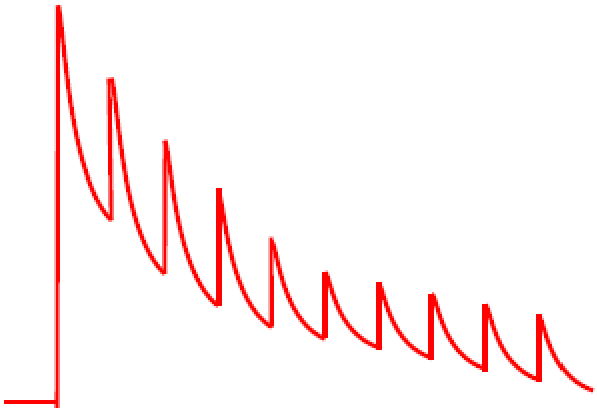
- Catching a prey

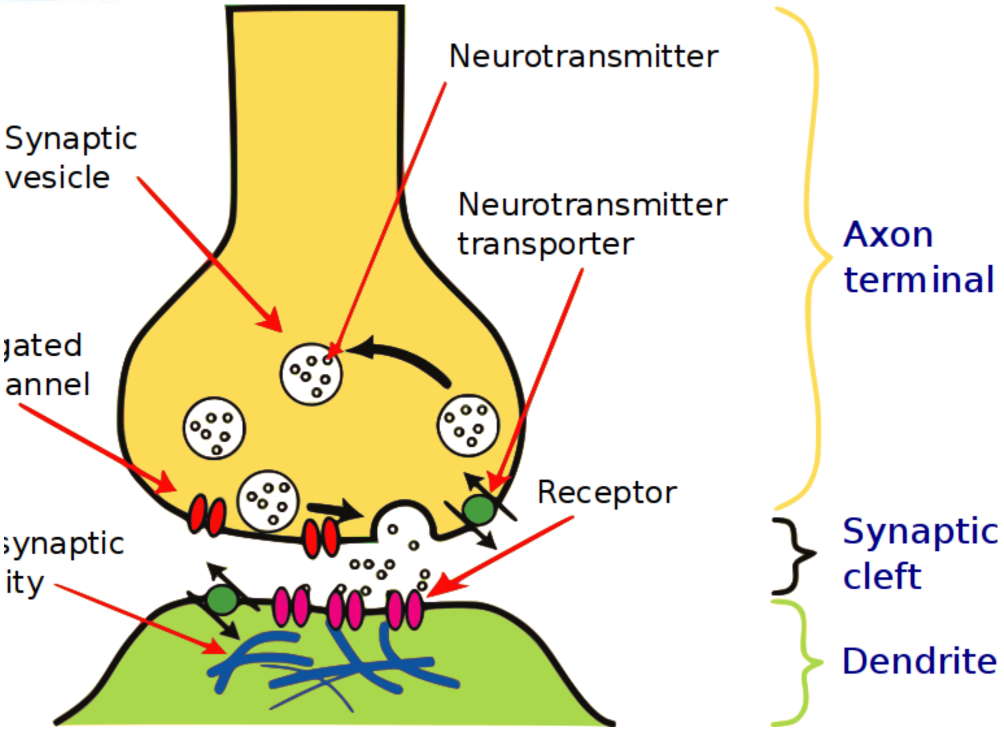
- Escaping from a predator

Negative Feedback Mechanisms

- Short-term synaptic depression (STD)
  - Degradation of synaptic couplings due to consumption of neurotransmitters after prolonged firing
- Spike Frequency Adaptation (SFA)
  - Desensitization of firing threshold after prolonged firing
- Inhibitory Feedback Connection from higher layers (IFL)

Short-term Depression (STD)





From Wikipedia

Tsodyks and Markram (1997)
Tsodyks, Pawelzik & Markram (1998)

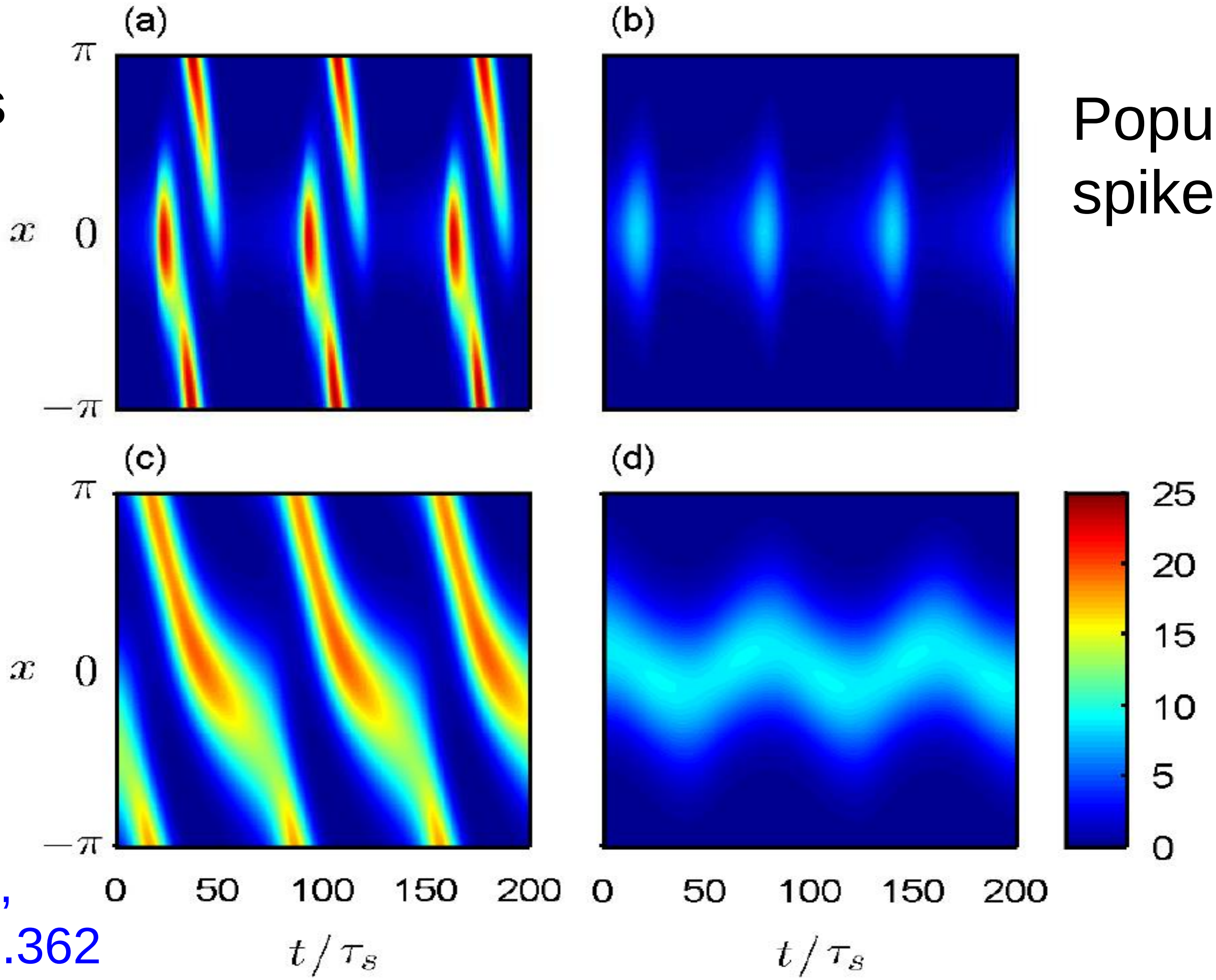
In the Presence of Stimuli

Emitters

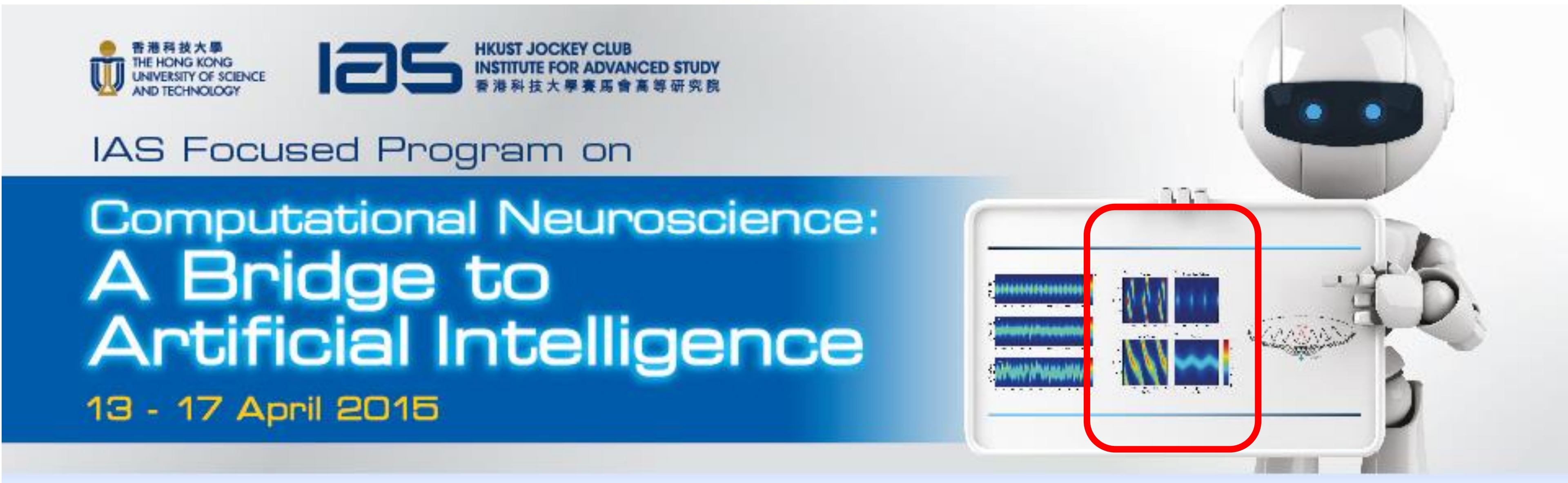
Population spikes

Moving bumps

Sloshers



Wang et al., arXiv/ 1502.362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Artificial Intelligence
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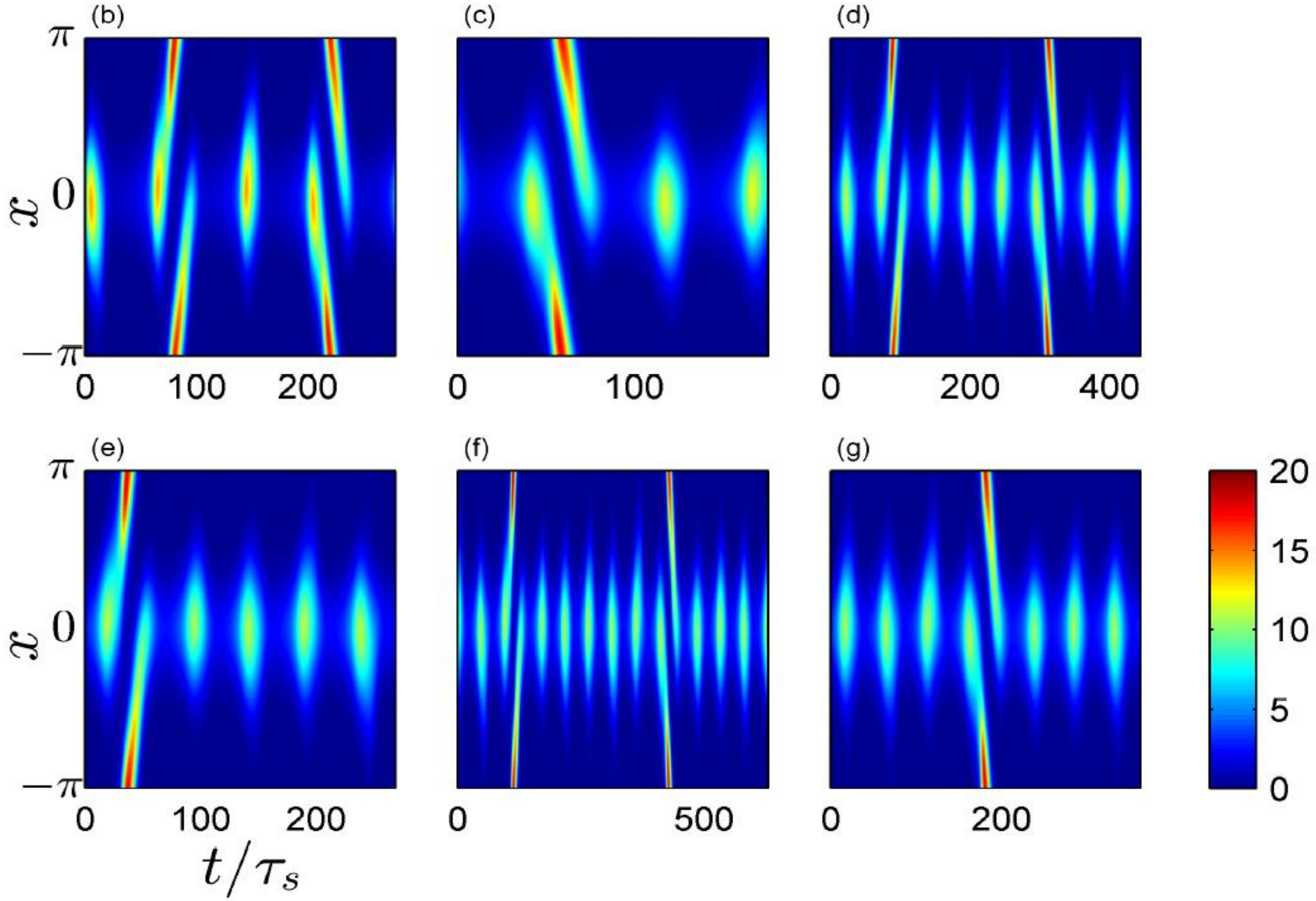
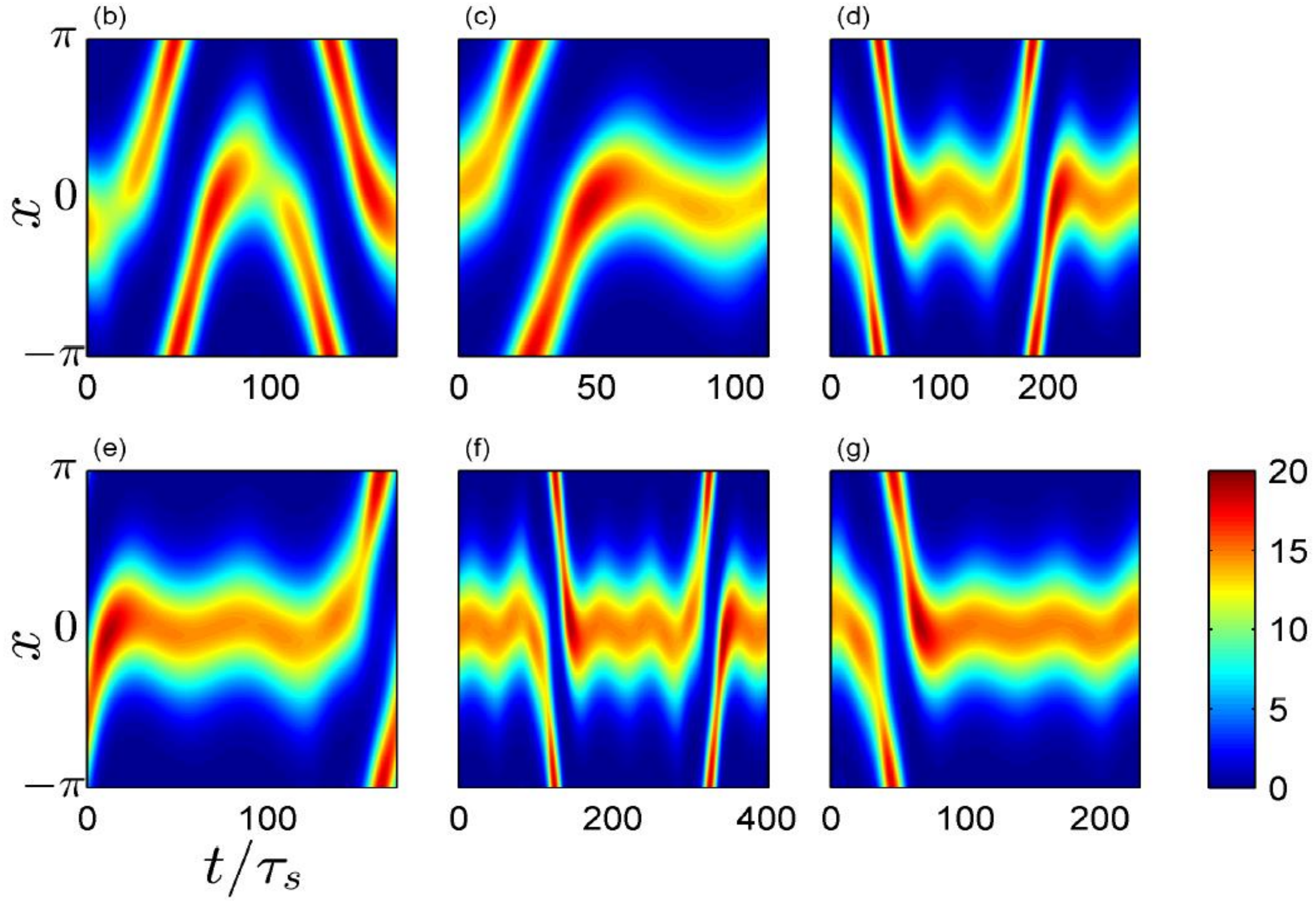
Mixtures of Emitters and Population Spikes



Mixtures of Moving Bumps and Sloshers



- **Now focus on moving bumps, most useful for tracking moving stimuli.**
- **In general, the moving bumps lag behind external stimuli, as shown in the flash lag effect.**

next→

←prev

Flash-Lag Effect

From Michael's "Visual Phenomena & Optical Illusions"

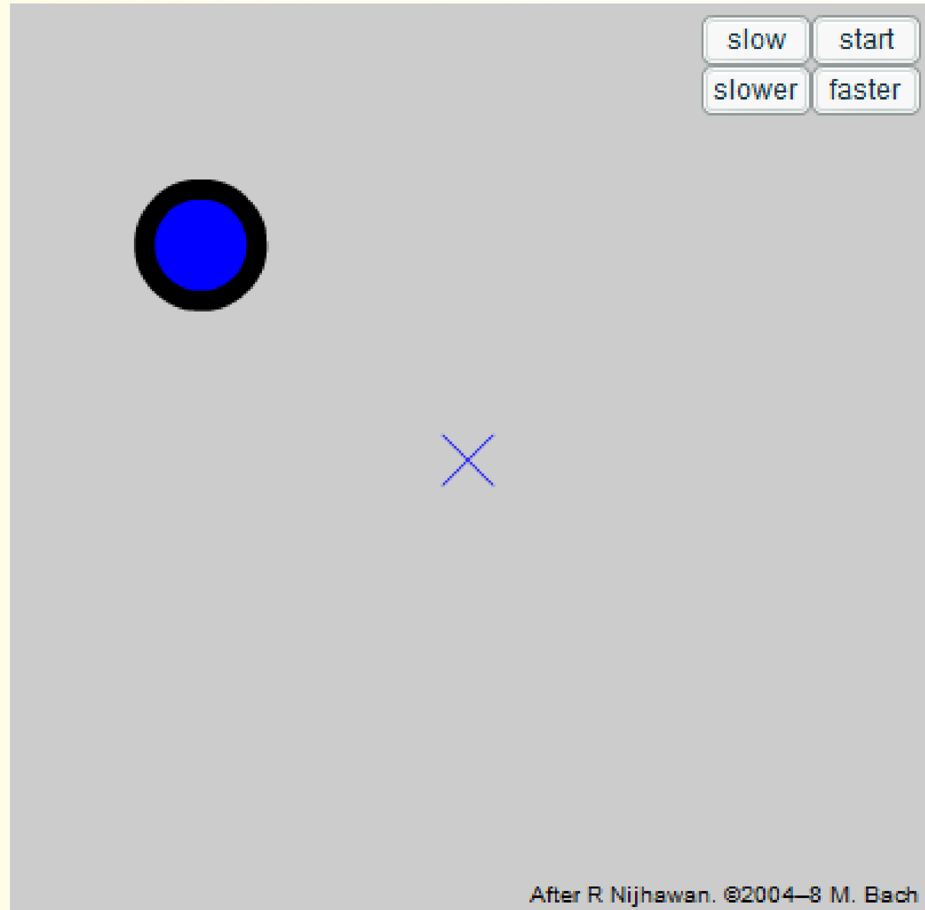
Warning: this is a subtle effect.

What to do

Fixate on the cross, but watch the moving ring. In other words: dissociate gaze direction and attention; this takes some practice.

What to observe

By now you will have noticed that the blue content of the ring is occasionally replaced by a yellow shape. Is it a full yellow disk or a yellow crescent? If you fixate on the cross, you should only see a crescent. If you follow the ring, you see the full disk. TLC (=tender loving cooperation) required ;-) [in other words: the effect can be somewhat subtle].



http://www.michaelbach.de/ot/mot-flashLag/index.html

Nijhawan, R. Nature 370, 256-257 (1994).

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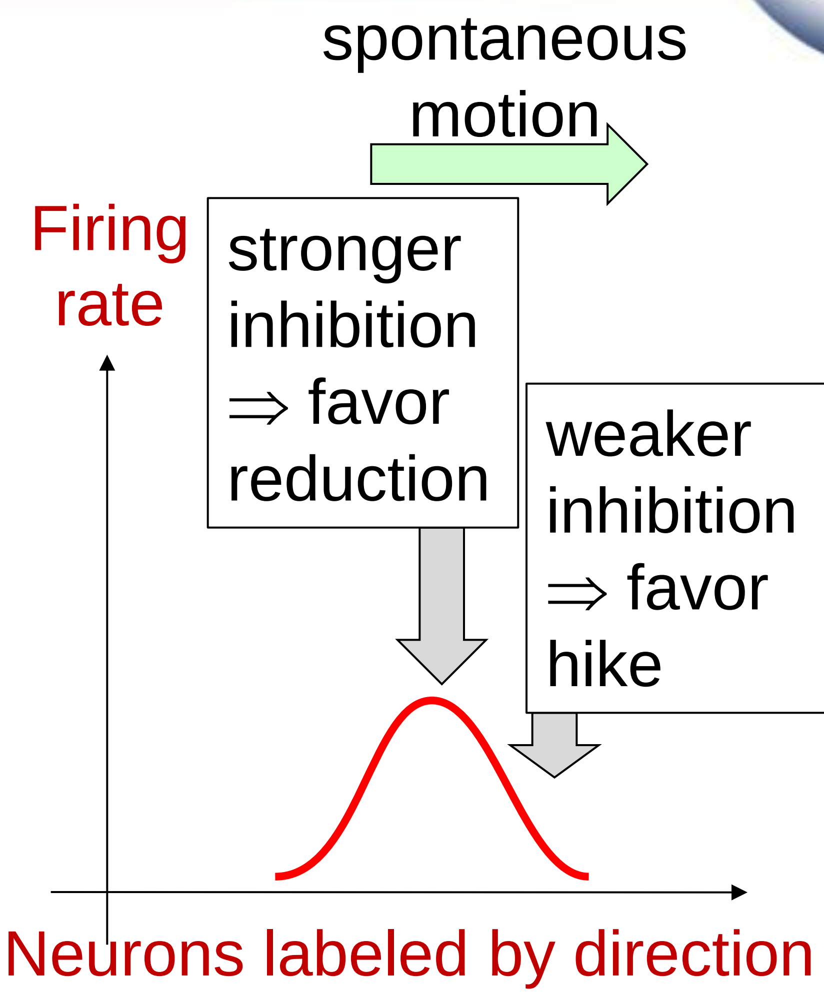
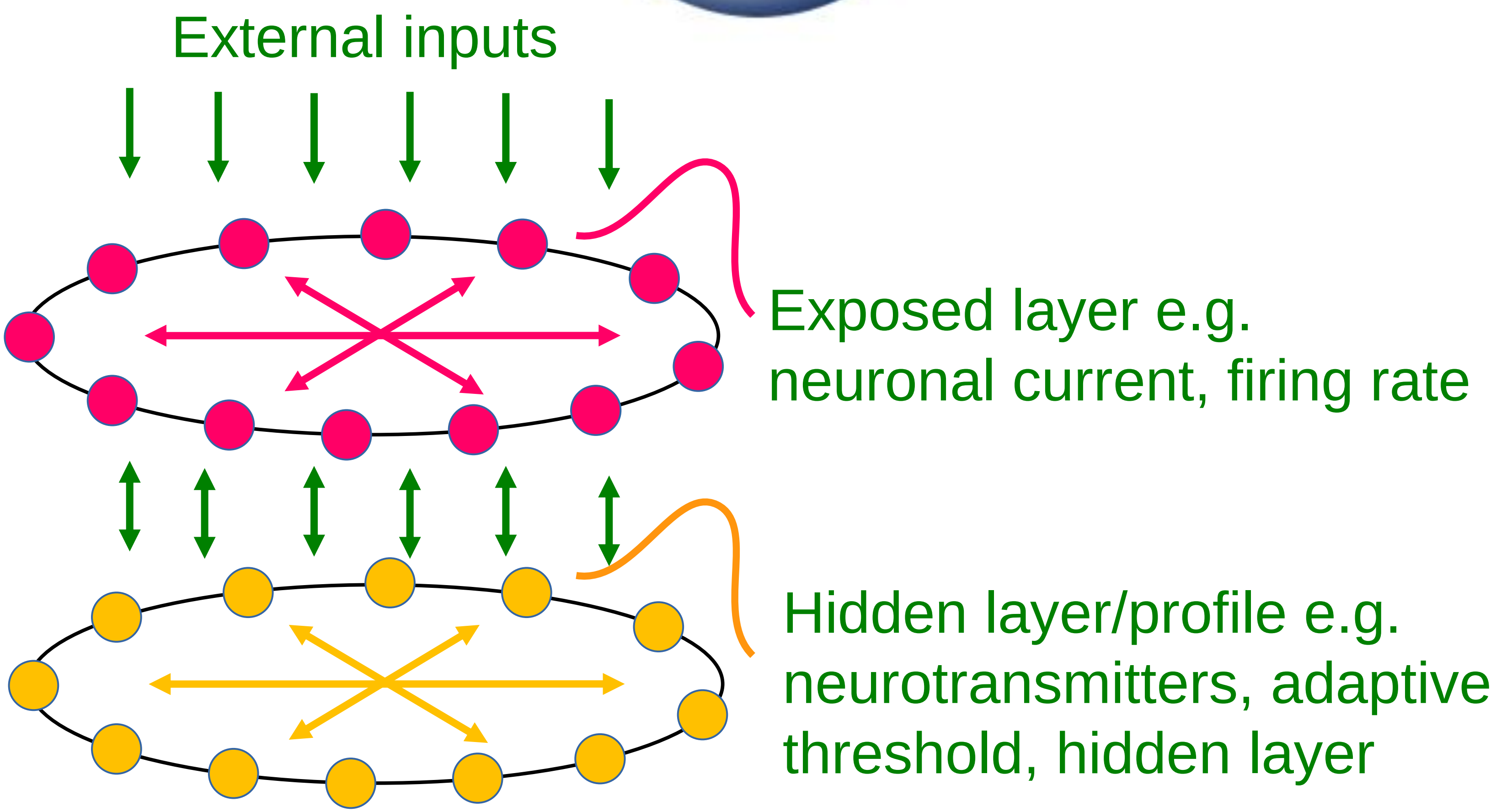
Intrinsic: Spontaneous Motion



- Spontaneous motion is caused by the presence of slow, localized, negative feedback (to be explained)
- Slow: the dynamics of building up the bump is not affected
- Localized: strong inhibition in active regions, weak inhibition in less active regions
- ⇒ increased mobility

Neural Field Models



General Applicability

- Our results (in the next few slides) are applicable to any network structure as long as they satisfy these conditions:
  - (1) The dynamical equation is the same when the coordinates are displaced (translationally invariant).
  - (2) The dynamical equation is the same when the coordinates are reflected about the origin (inversion symmetry).
  - (3) There exists a non-zero steady-state solution of the exposed and hidden profiles symmetric with respect to an axis of symmetry (even parity).

Result 1: Lagging/leading ~ position stability/instability

- When the bump leads/lags the moving stimulus, anticipation time is +/-.
- Anticipation time: $\tau_{ant} = \tau_{stim}\tau_{int}\lambda$

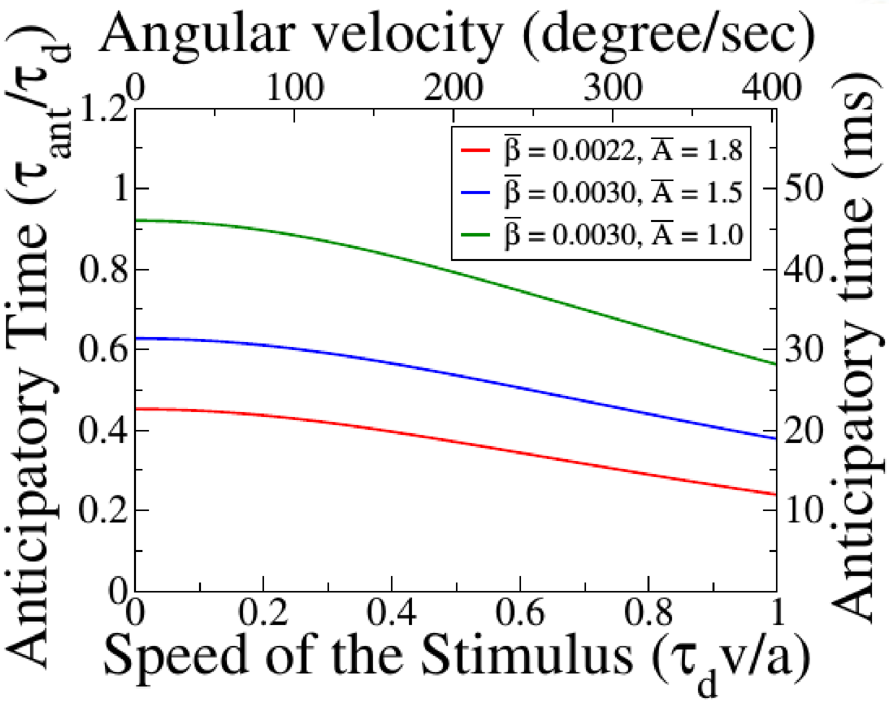
  extrinsic **intrinsic**

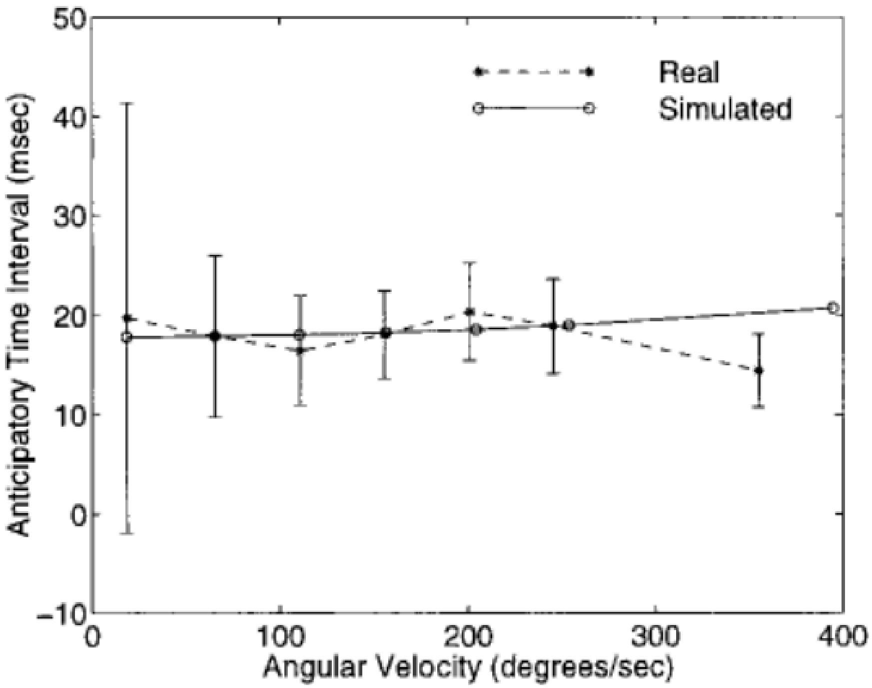
- τ_{stim} = time scale for the stimulus to build the bump, proportional to (stimulus strength)/(bump height).
- τ_{int} = the time lag of the hidden profile behind the exposed profile
- λ = instability eigenvalue of the profile separation between the exposed and hidden profiles
- In the static phase, the bump lags behind the moving stimulus; in the moving phase, the bump leads the moving stimulus for weak and slow stimulus.

Result 2: Anticipation time = constant

- Anticipation time: $\tau_{\mathrm{ant}} = \tau_{\mathrm{stim}} \tau_{\mathrm{int}} \lambda$
- <u>Anticipation time is effectively independent of velocity</u>

Anticipation Observed in Neural Systems



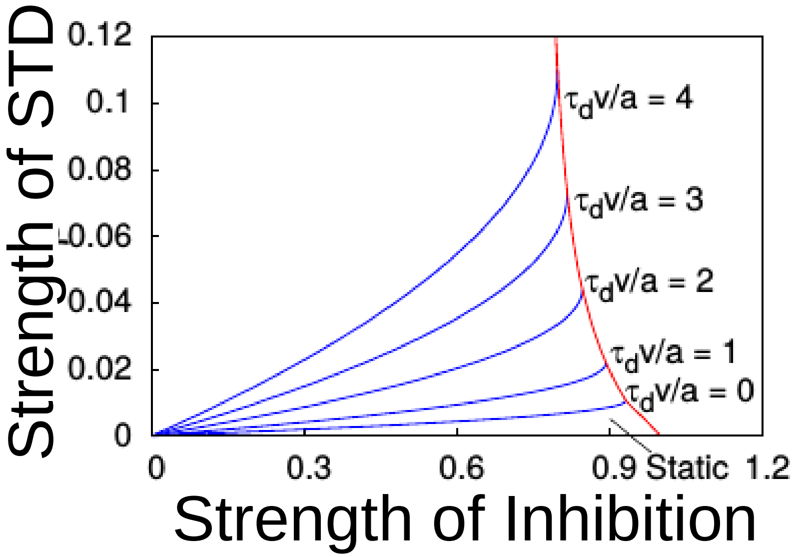


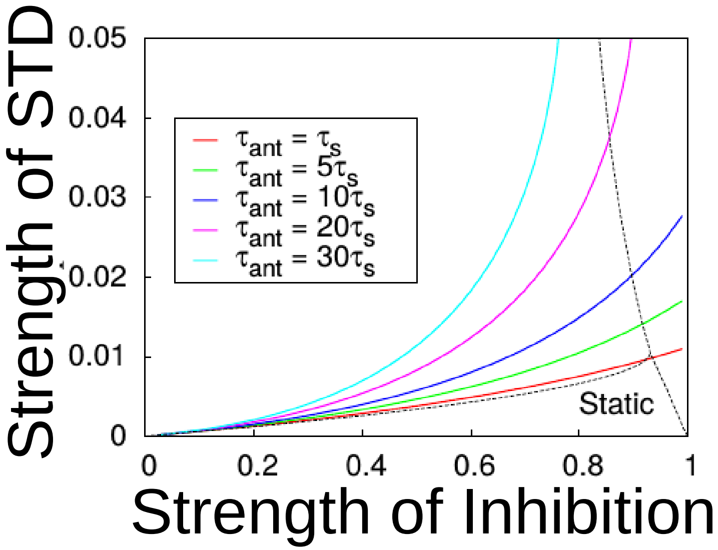
Prediction
Fung, Wong & Wu (2012)

HD experiment in rodents
Goodridge & Touretzky (2002)

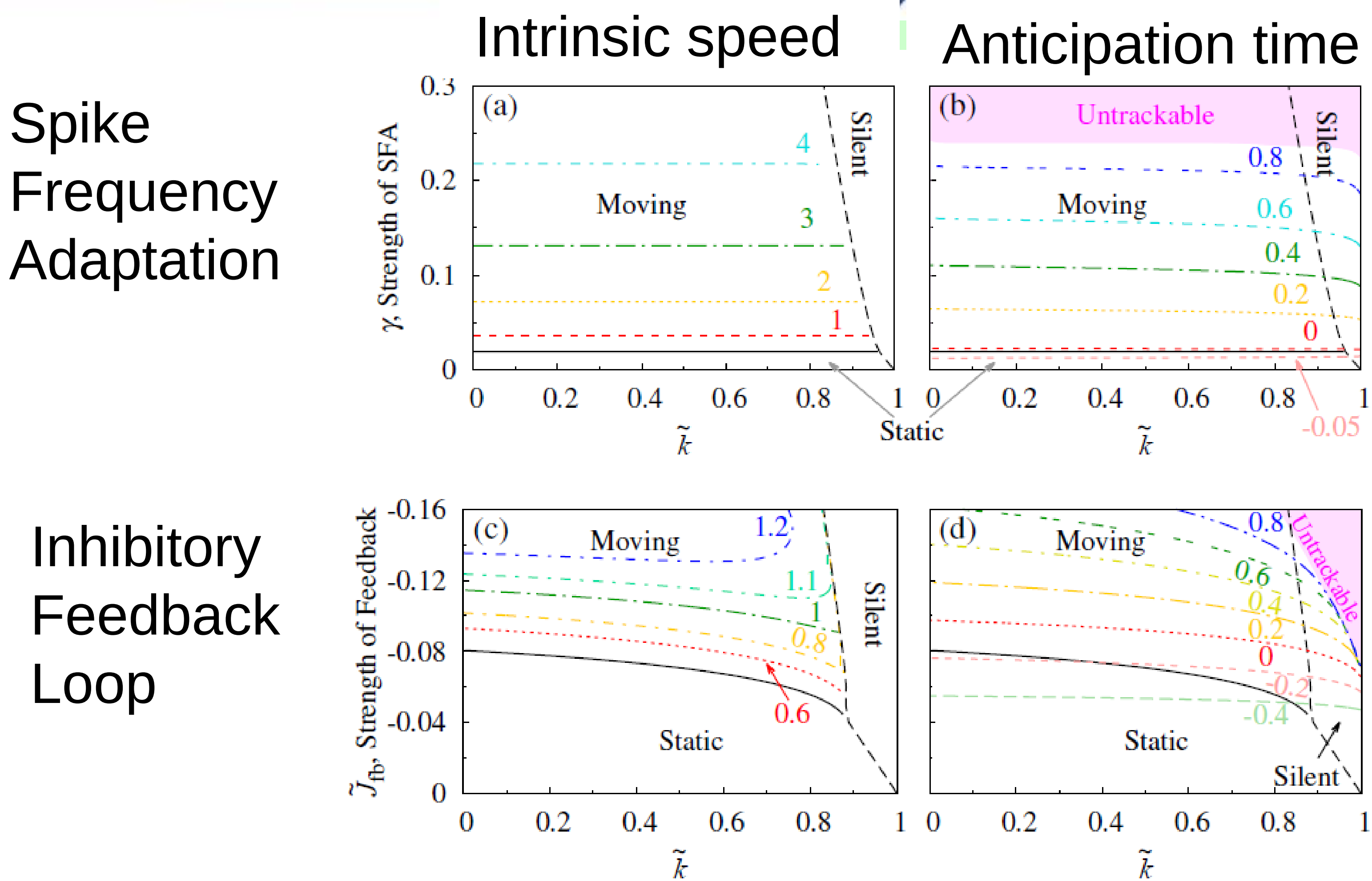
Result 3: Anticipation time ~ intrinsic speed²

- In the moving phase, $$\tau_{\text{ant}} = \frac{\tau_{\text{stim}}\tau_{\text{int}}^{3}}{K} v_{\text{int}}^{2}$$
- The contours of constant anticipation time and constant intrinsic speed correspond to each other.





Same for SFA and IFL



Conclusion

- The fluctuation-response relation relates the intrinsic and extrinsic behaviors in neural fields.
- Applicable to neural systems in general.
- Physical principles underlying both artificial and biological neural information processors.

Thank you!