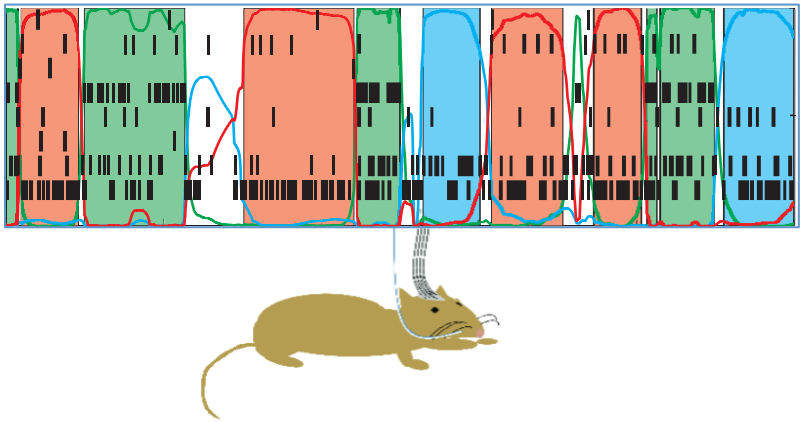
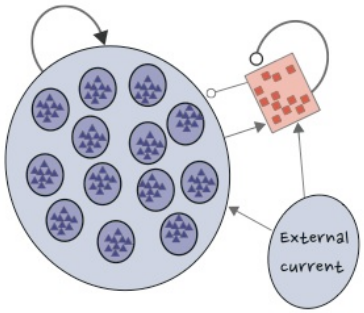
A bottom-up approach to modeling the sensory cortex

Luca Mazzucato

Neurobiology and Behavior

Stony Brook

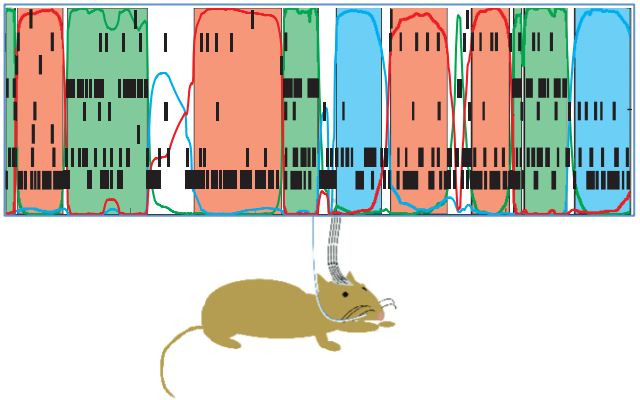




Brookhaven – January 19th 2016

Outline

- Neural activity in the sensory cortex
- The taste cortex
- Mechanistic model - recurrent neural network
- Model predictions vs. experiments



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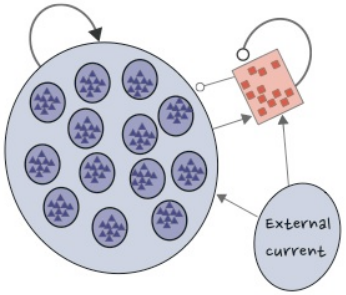
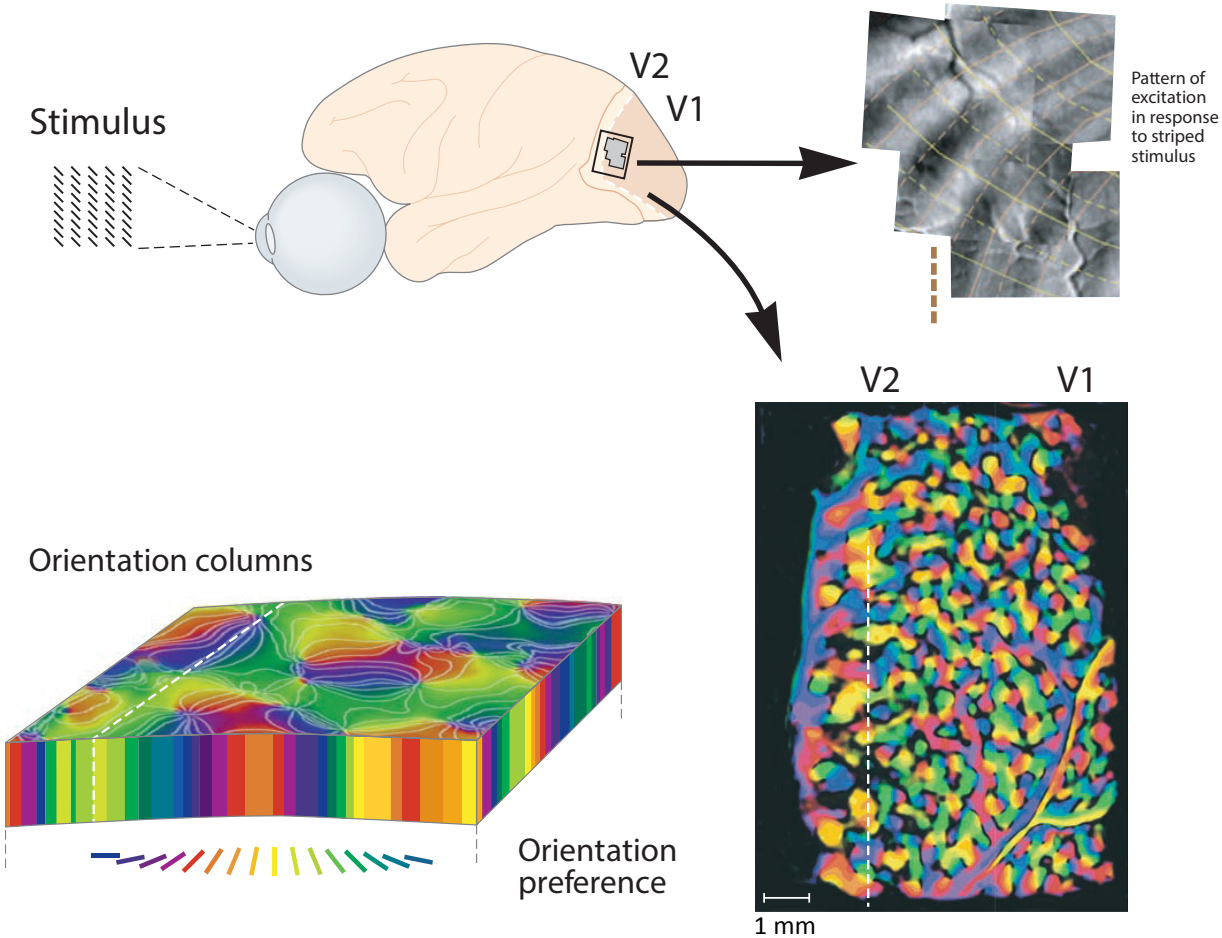


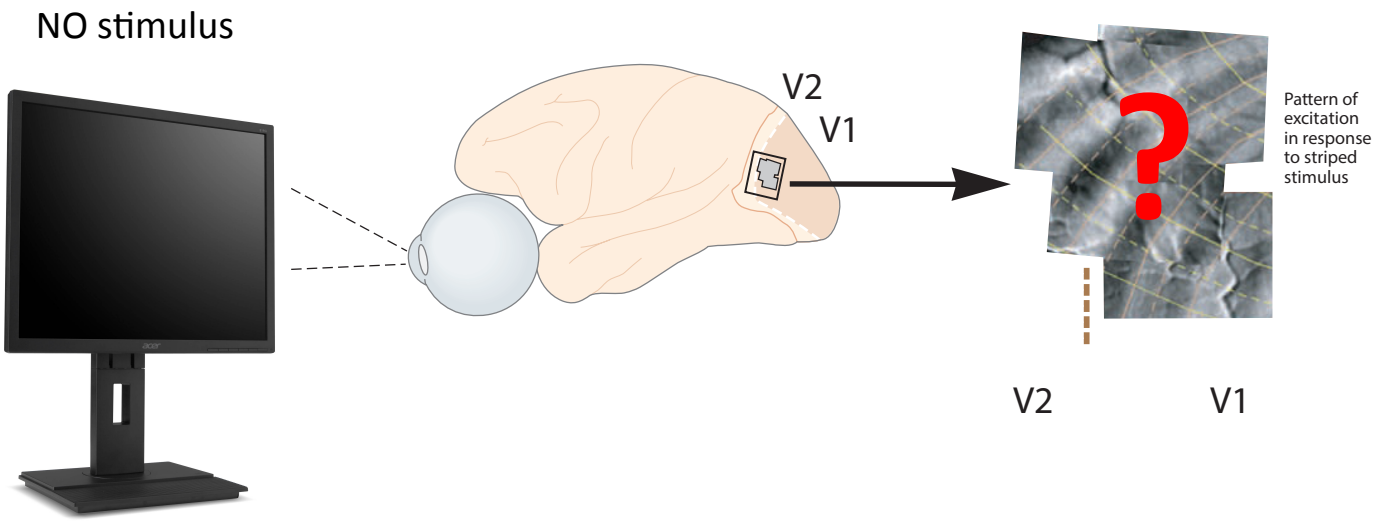
Recording from primary sensory cortex



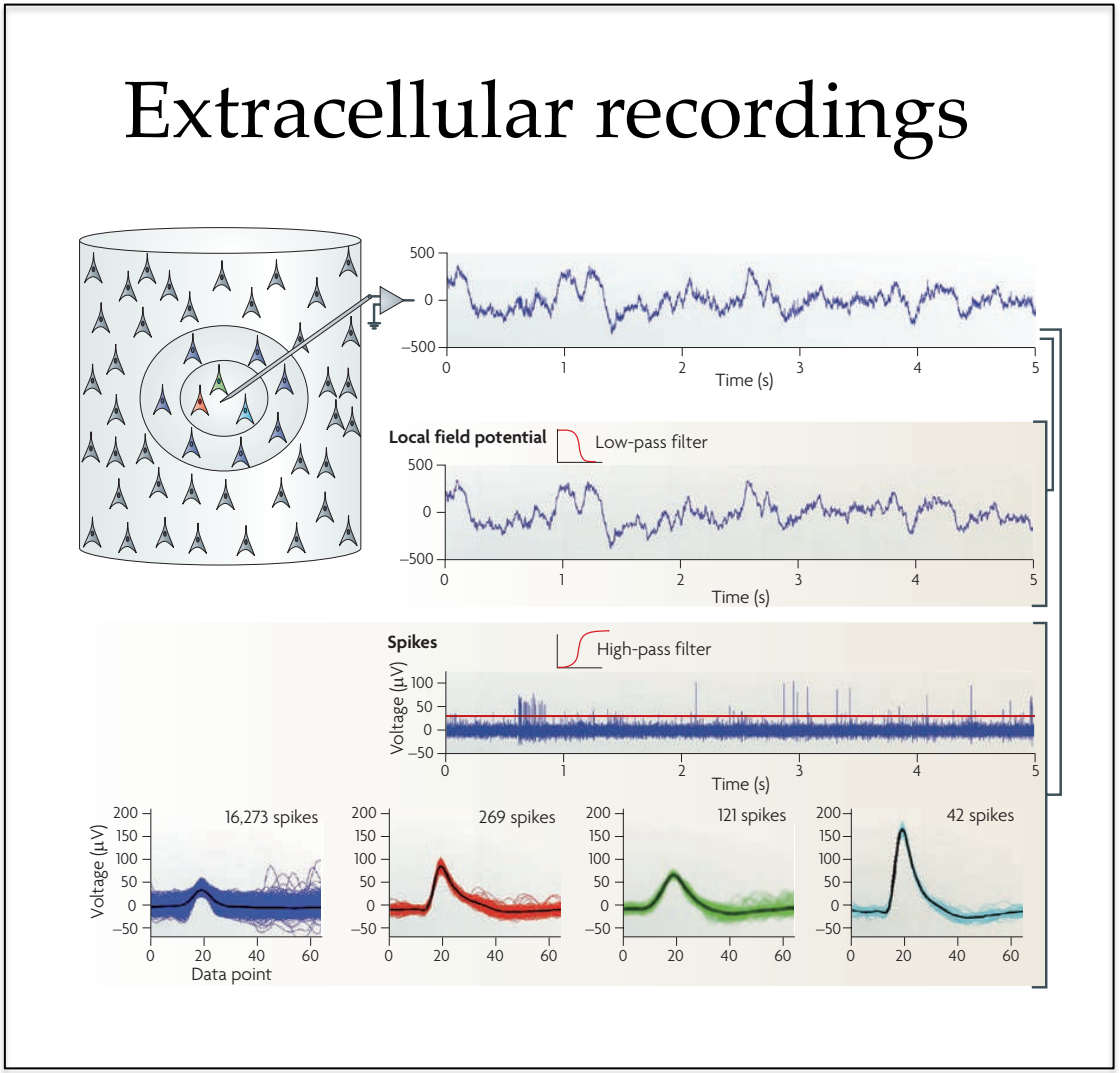
Kandel et al., 5th Ed.

Ongoing activity

Neural activity in the absence of overt sensory stimulation



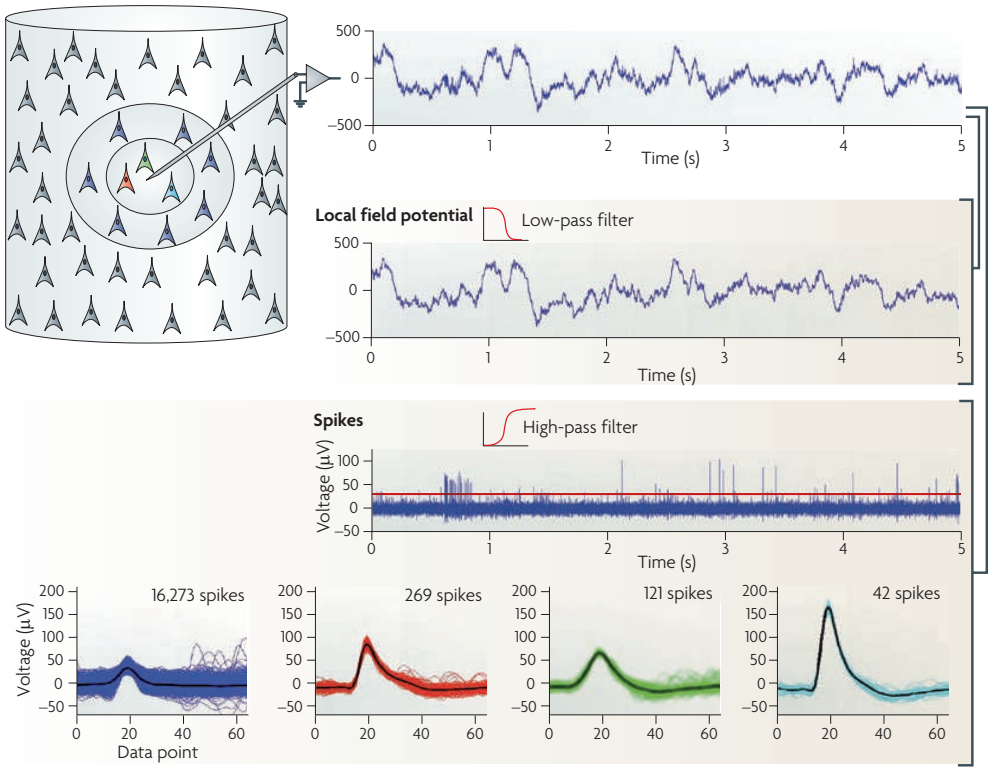
Recording from primary sensory cortex



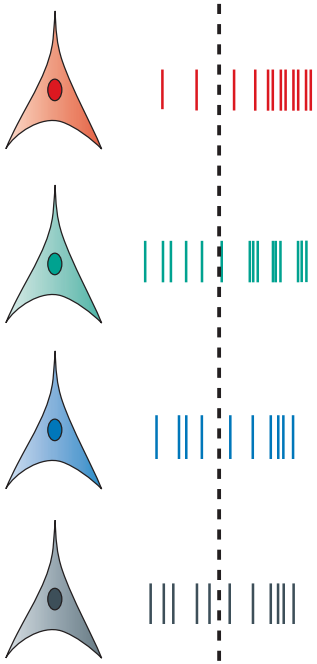
Quiroga et al., 2009

Recording from primary sensory cortex

Extracellular recordings



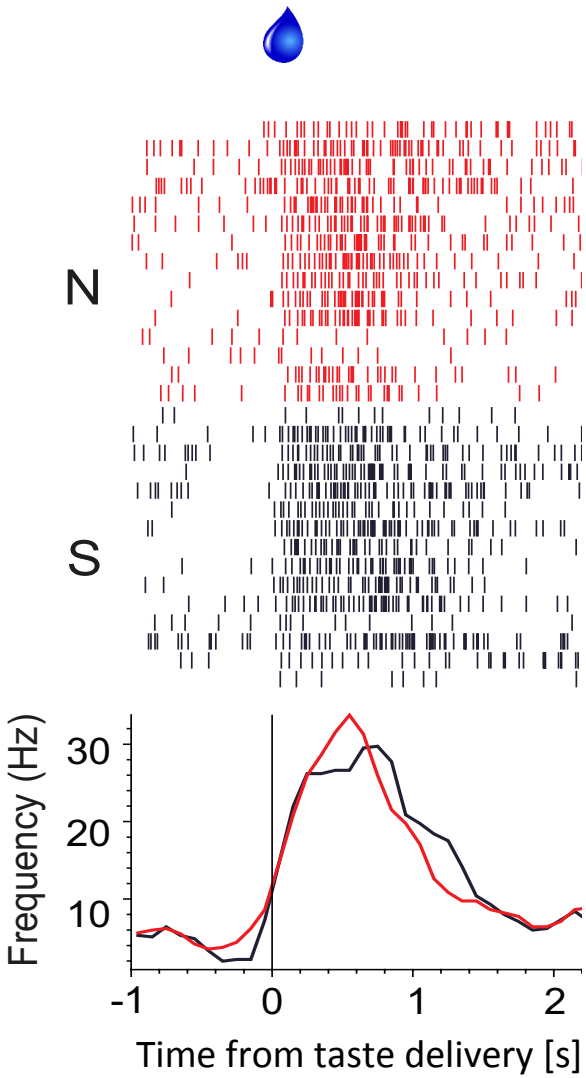
Spikes



Quiroga et al., 2009

Ongoing activity: noise?

Traditional view:

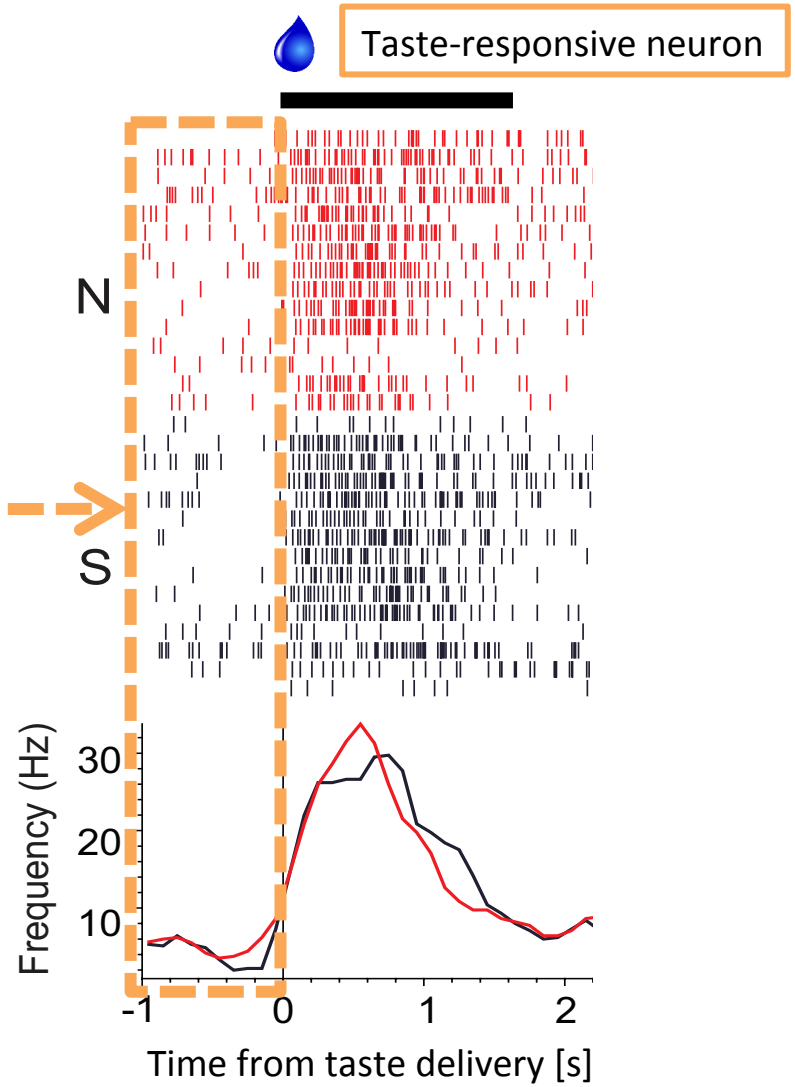


Jezzini*, Mazzucato* et al., 2013

Ongoing activity: noise?

Traditional view:

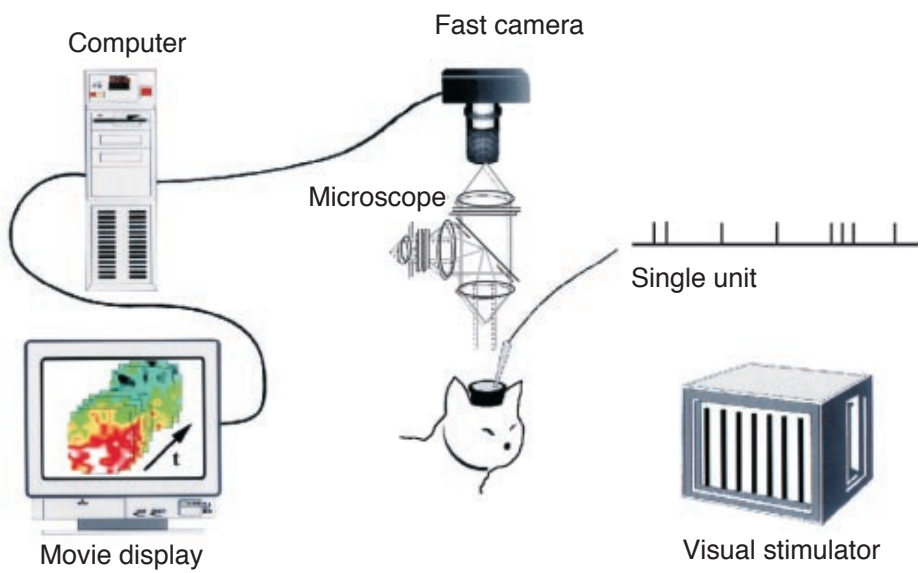
Ongoing activity
=
noisy baseline

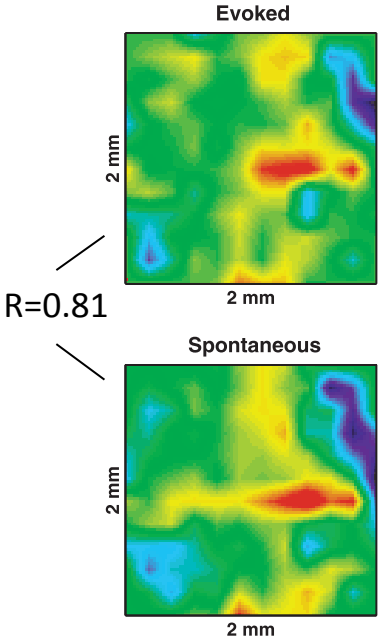


Jezzini*, Mazzucato* et al., 2013

Ongoing ⟷ Evoked

"Cortical states" during ongoing activity reproduce evoked orientation maps

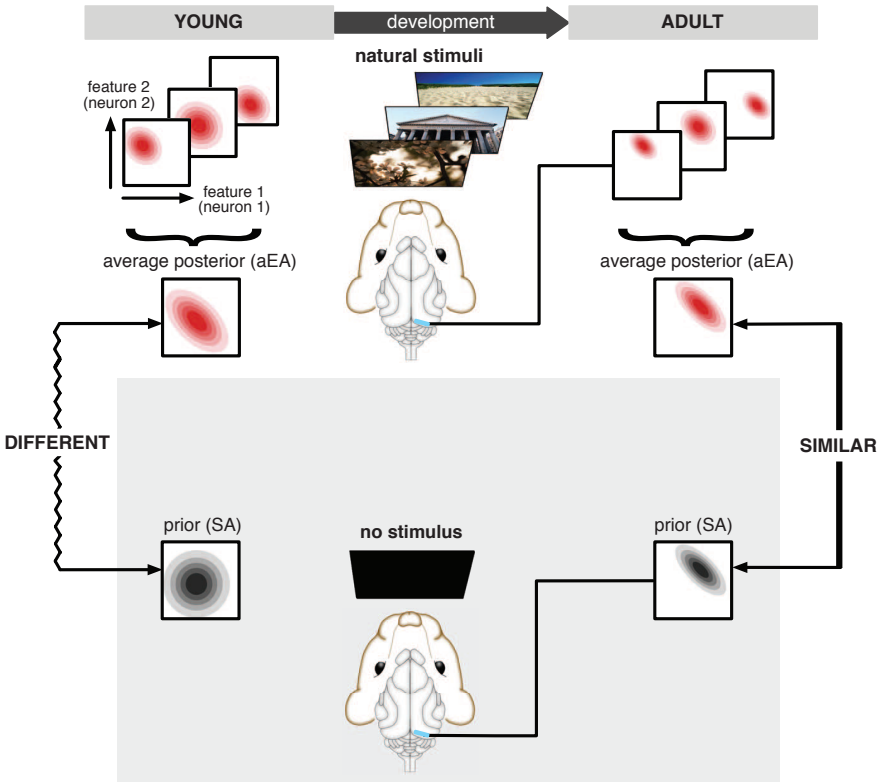




Arieli et al., 1996
Tsodyks et al., 1999
Kenet et al., 2003

Ongoing ⟷ Evoked

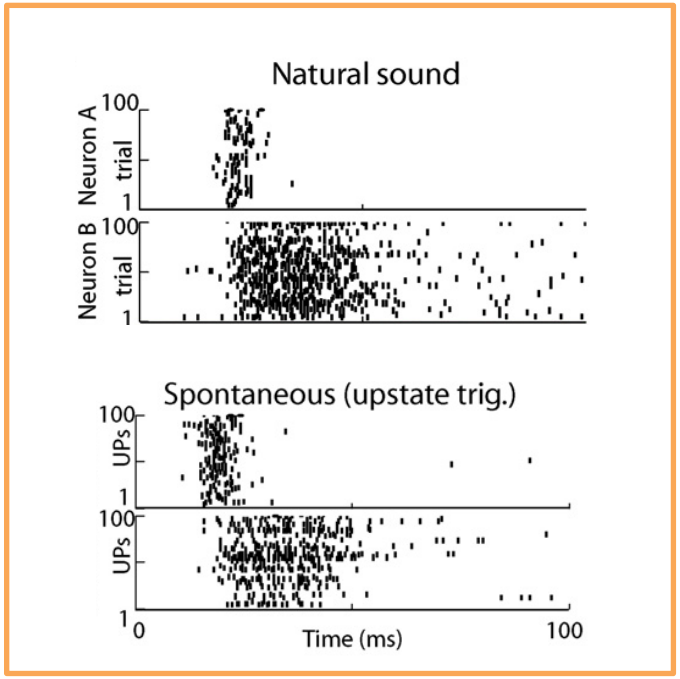
Prior distribution acquired during development?

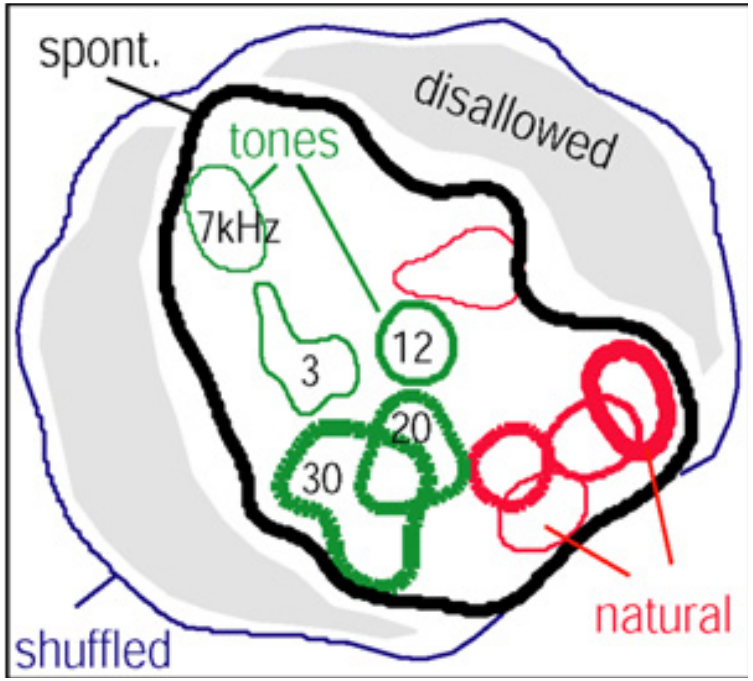


Fiser et al., 2004
Berkes et al., 2011

Ongoing ⟷ Evoked

Ongoing ⊃ evoked





Luczak et al., 2007, 2009, 2013

A unifying approach

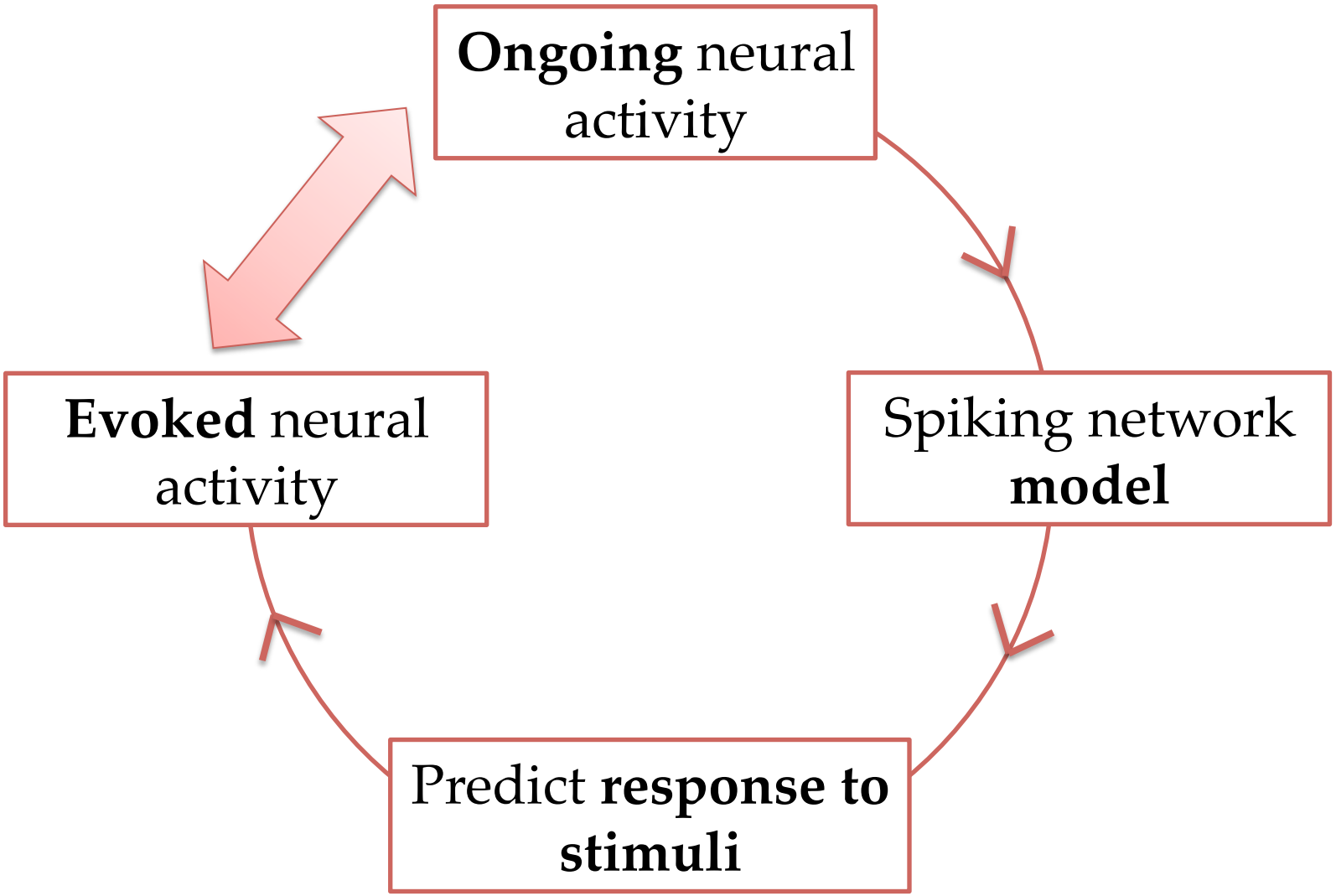
Ongoing neural activity

?

Evoked neural activity

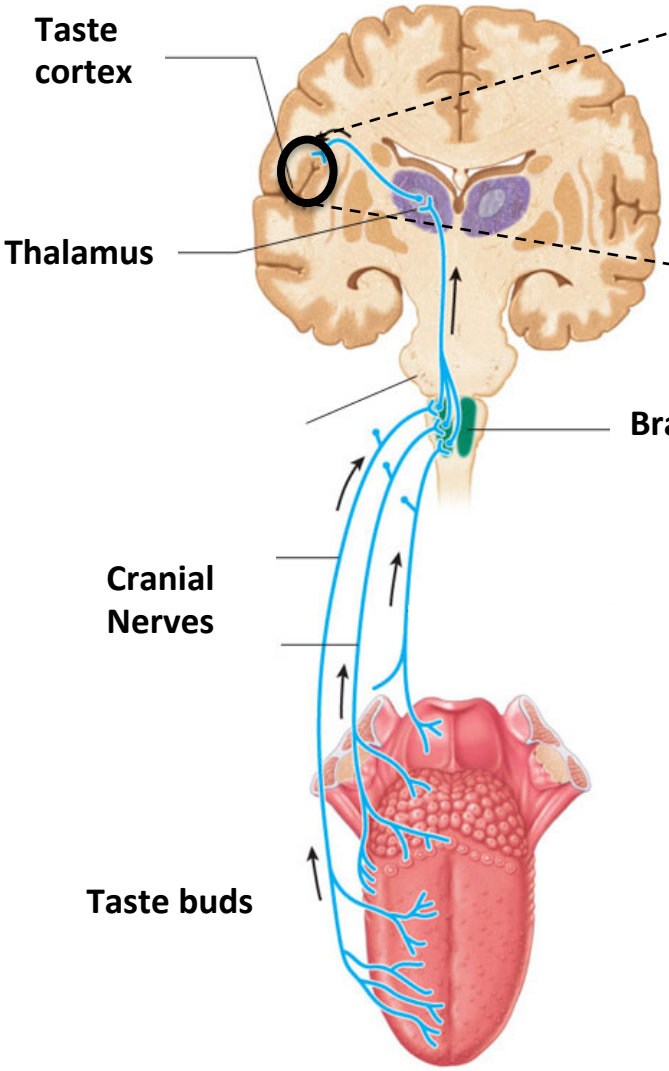
Mazzucato et al., 2015

A unifying approach

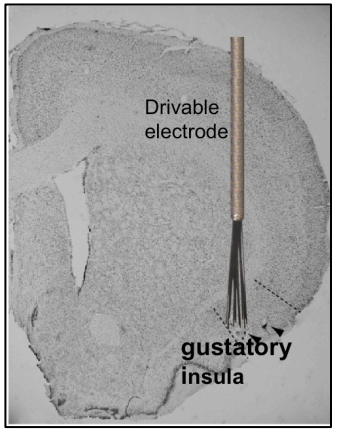


Mazzucato et al., 2015

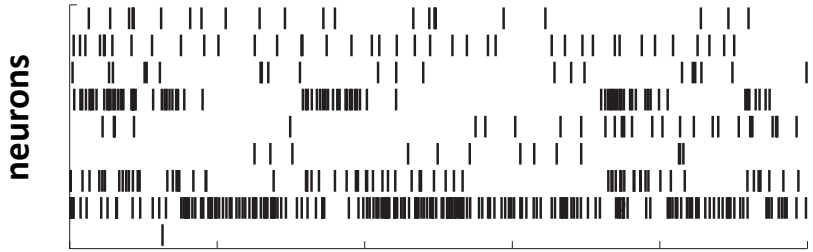
Taste Pathway



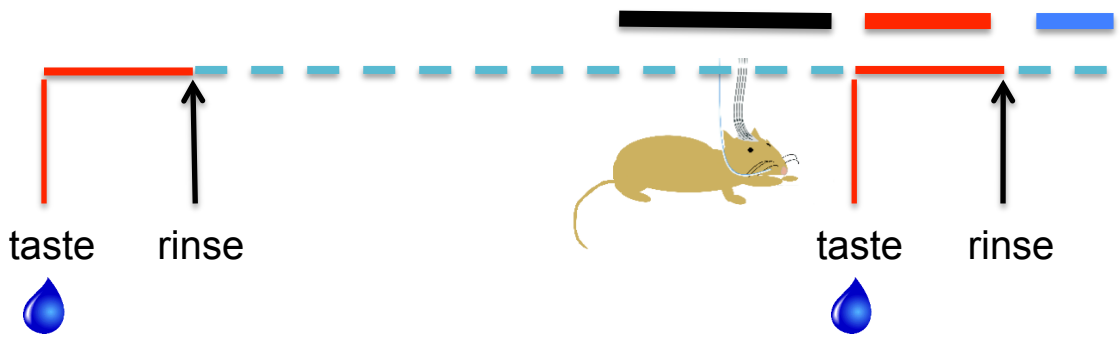
extracellular recordings



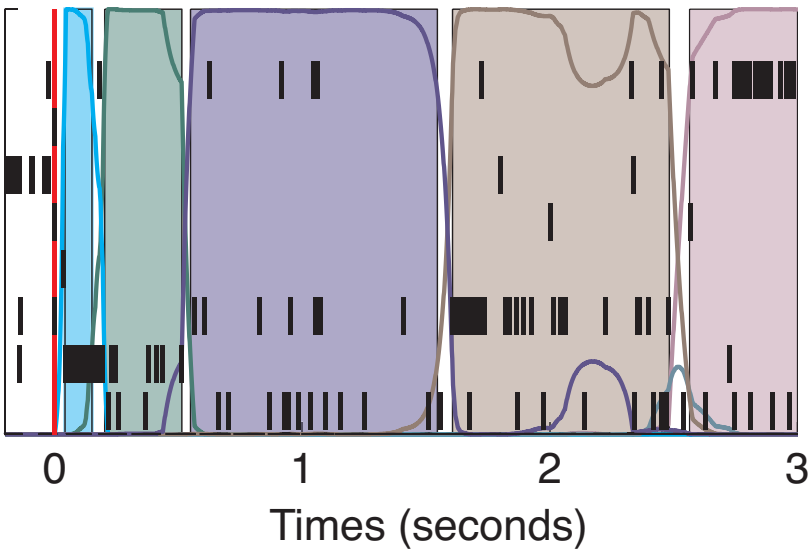
ensemble spike trains



Taste

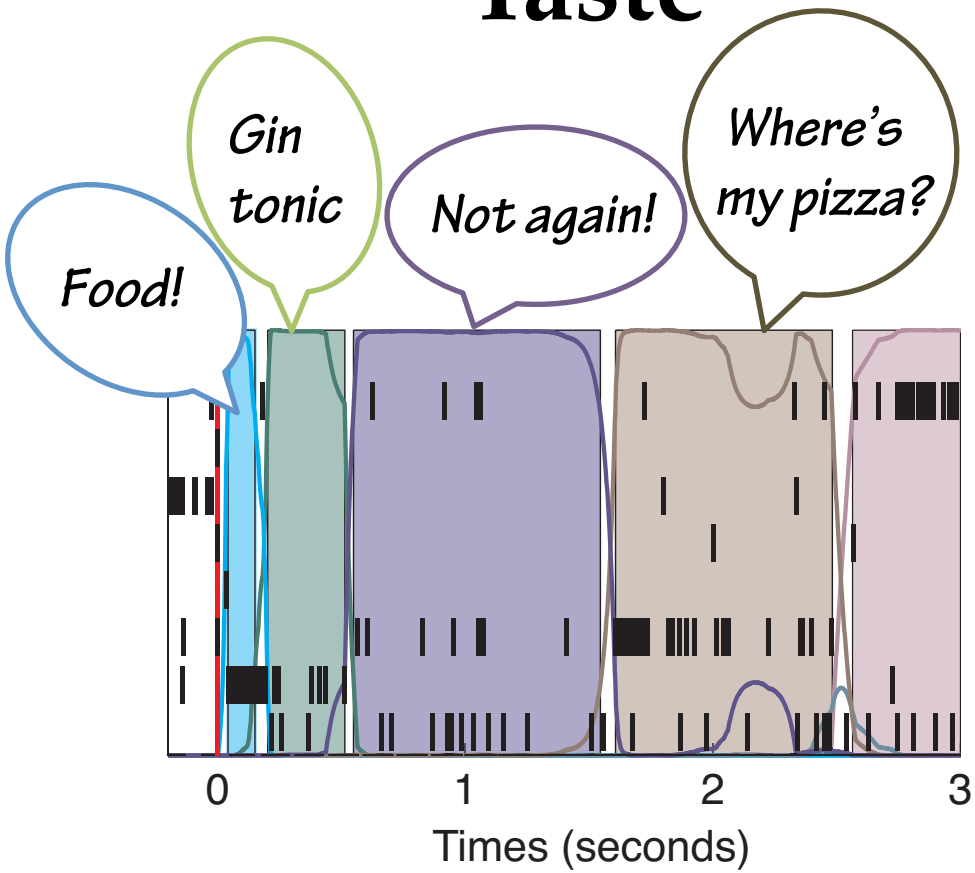


Taste



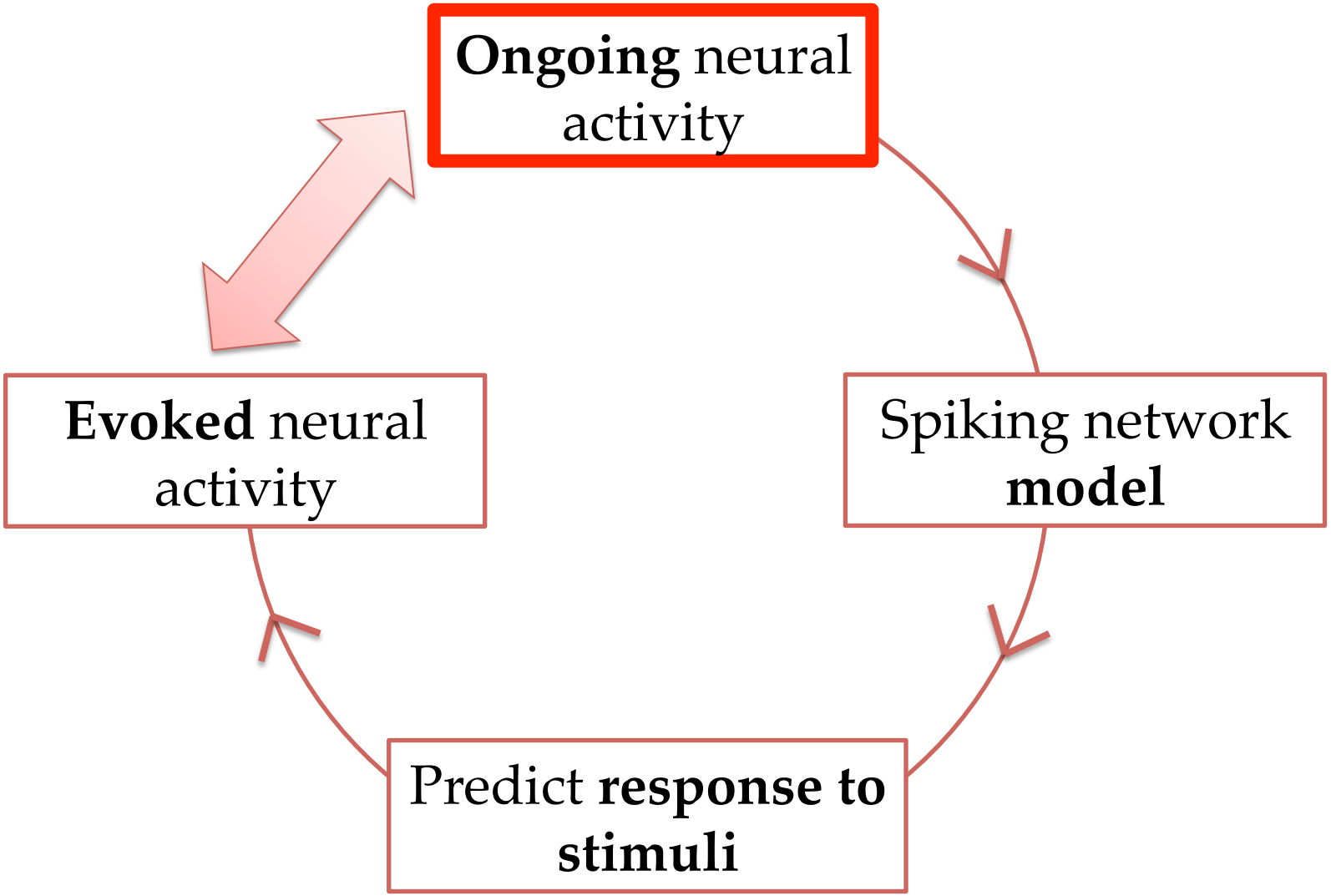
[Jones et al., 2007]

Taste

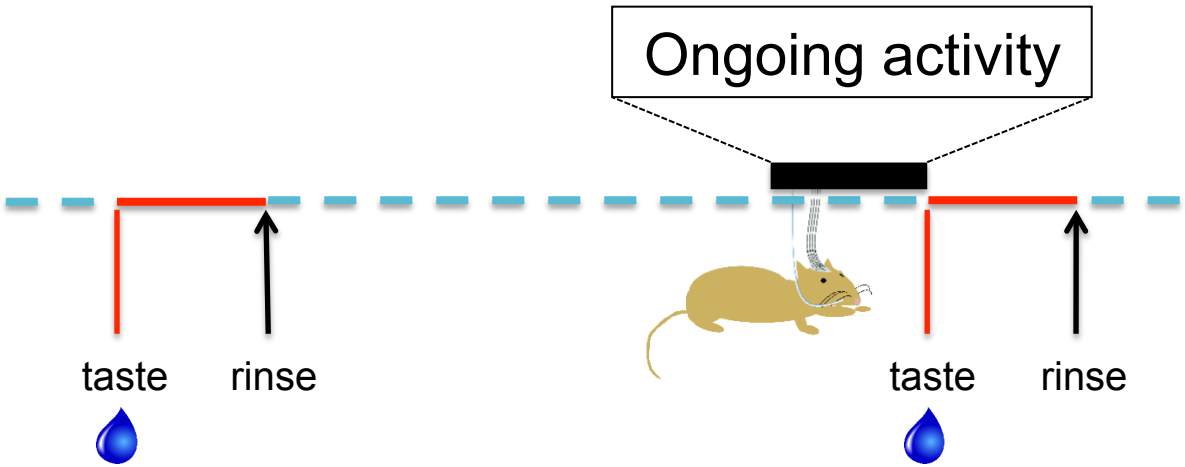


[Jones et al., 2007]

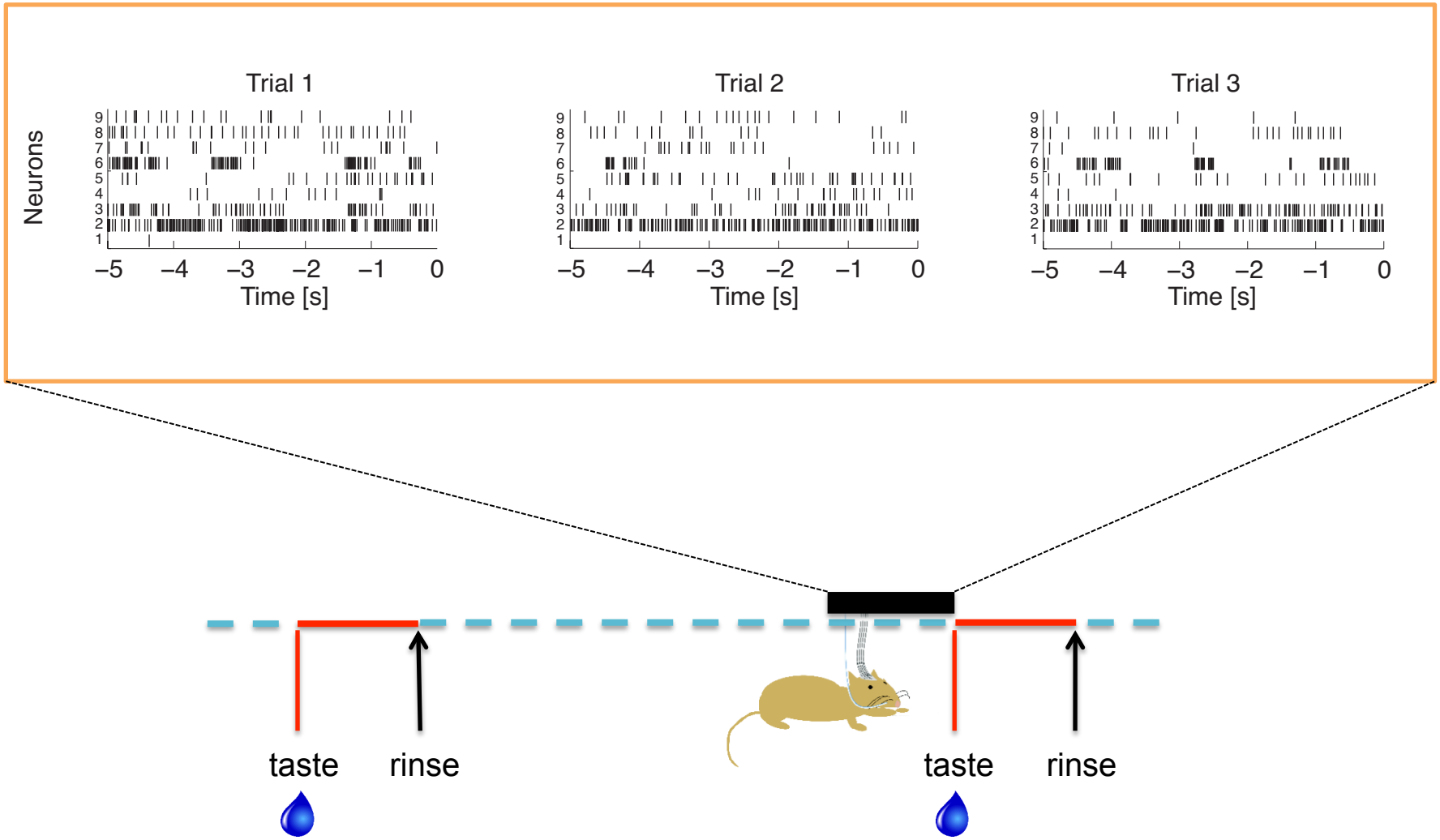
A unifying approach



Experiment

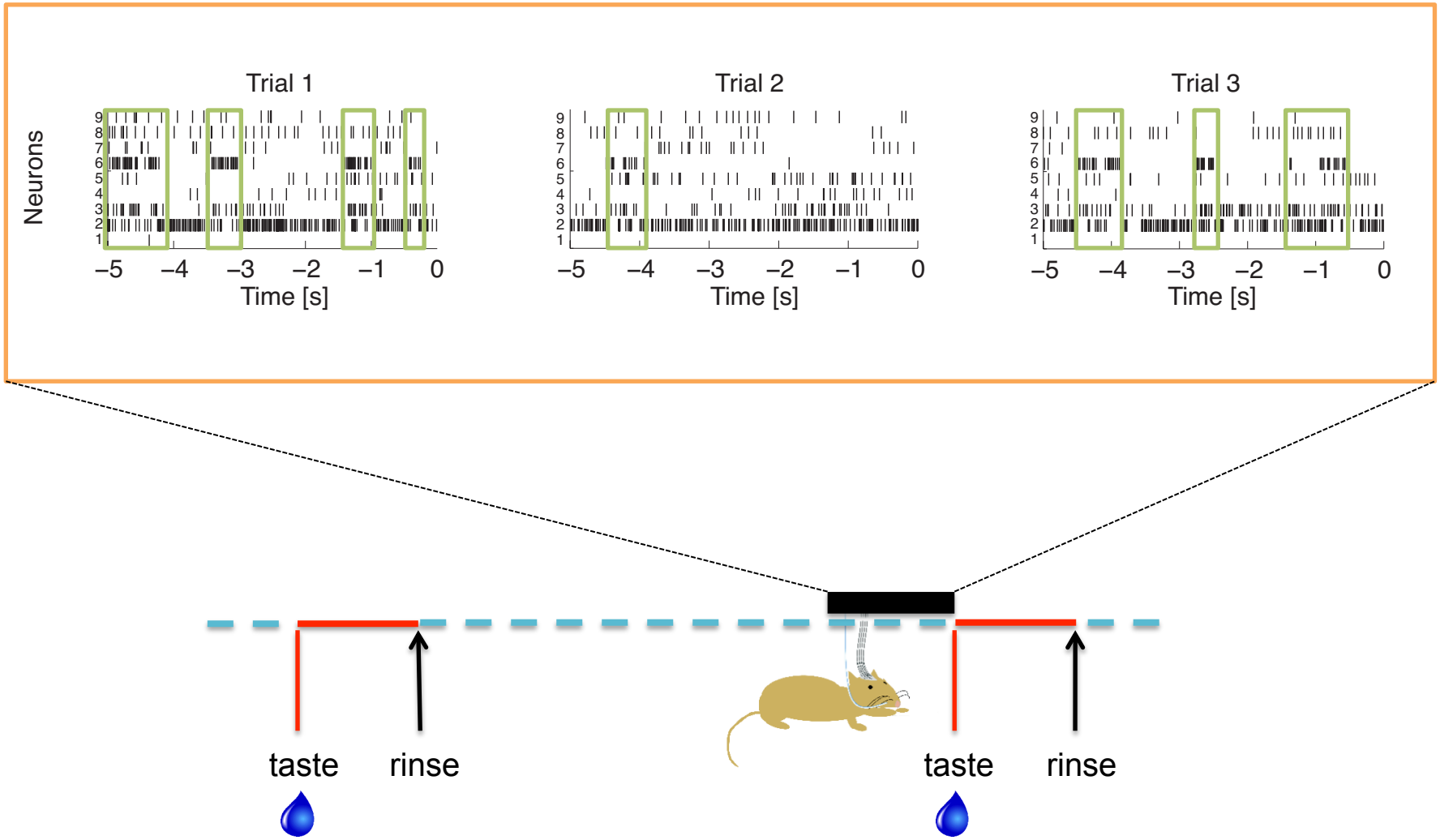


Ongoing activity



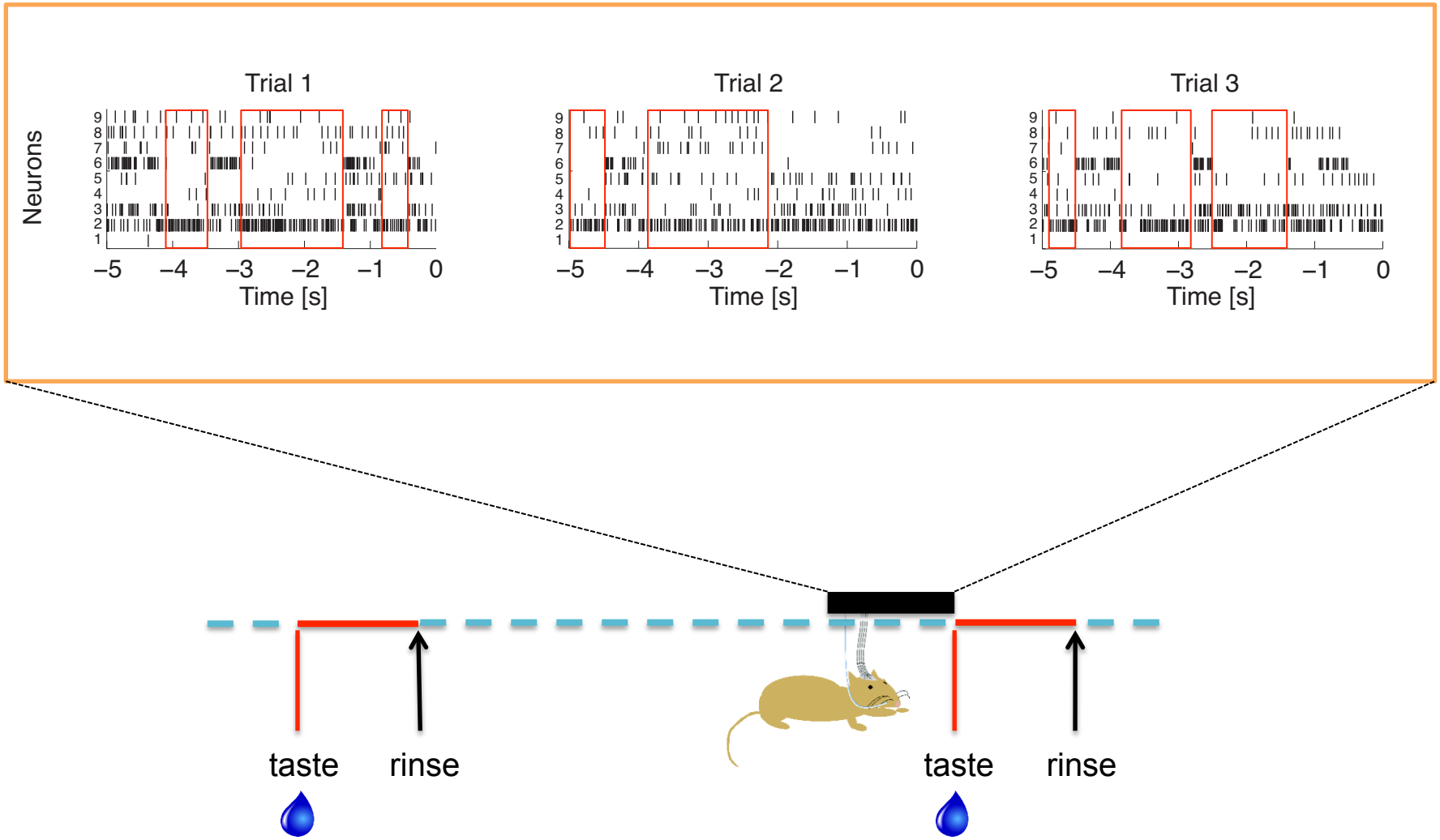
Mazzucato et al., 2015

Ongoing activity



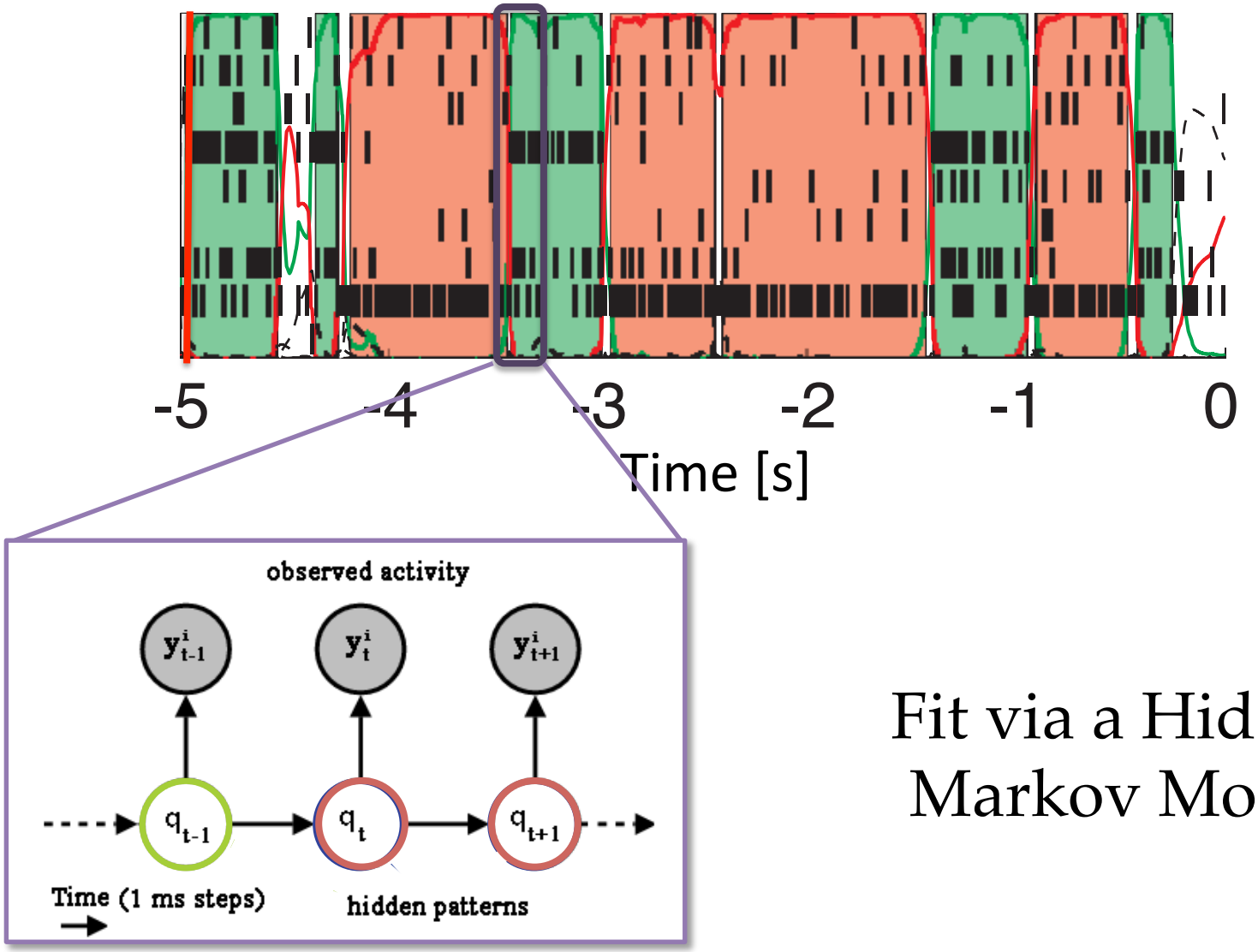
Mazzucato et al., 2015

Ongoing activity



Mazzucato et al., 2015

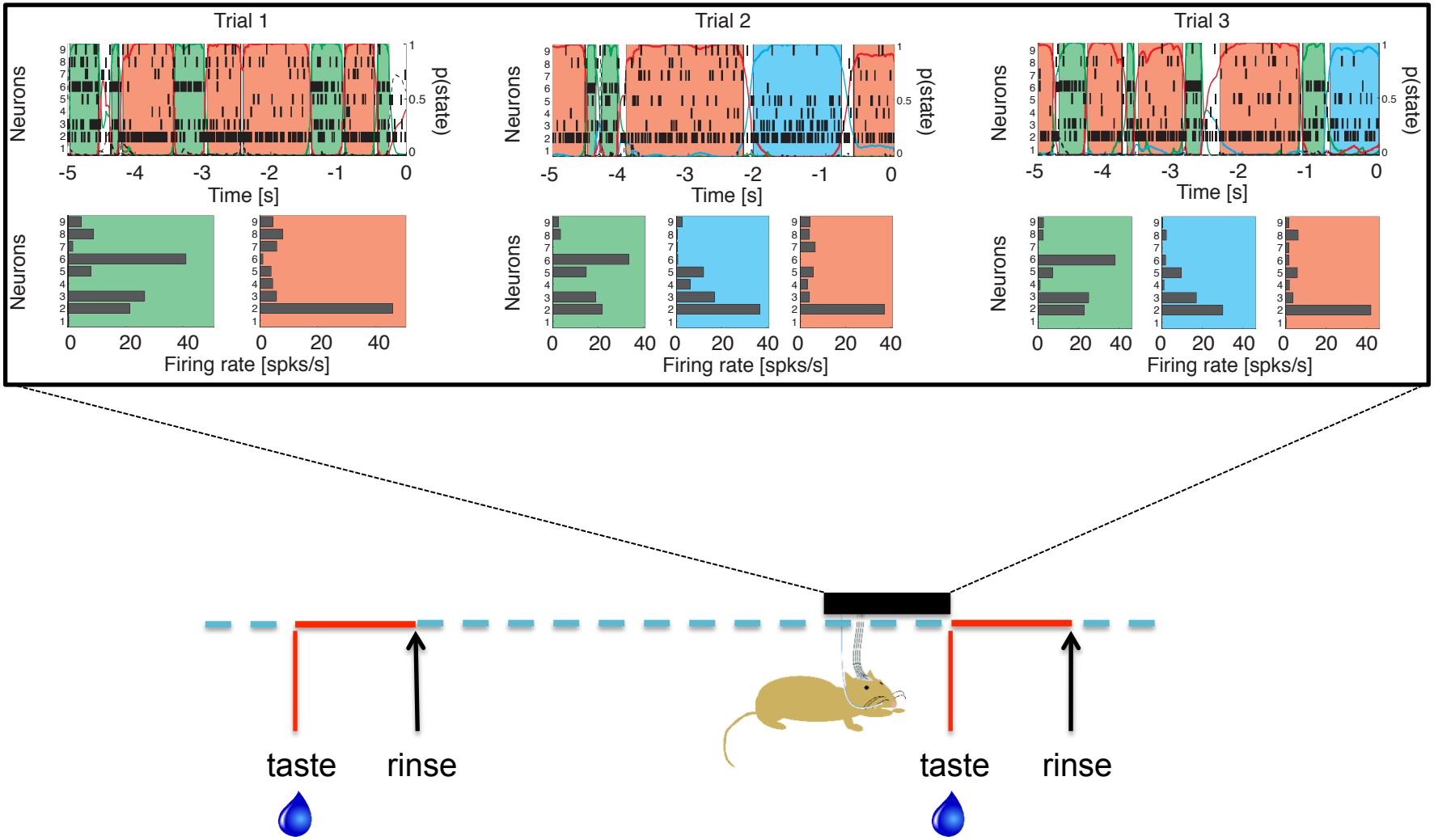
Ongoing activity



Fit via a Hidden Markov Model

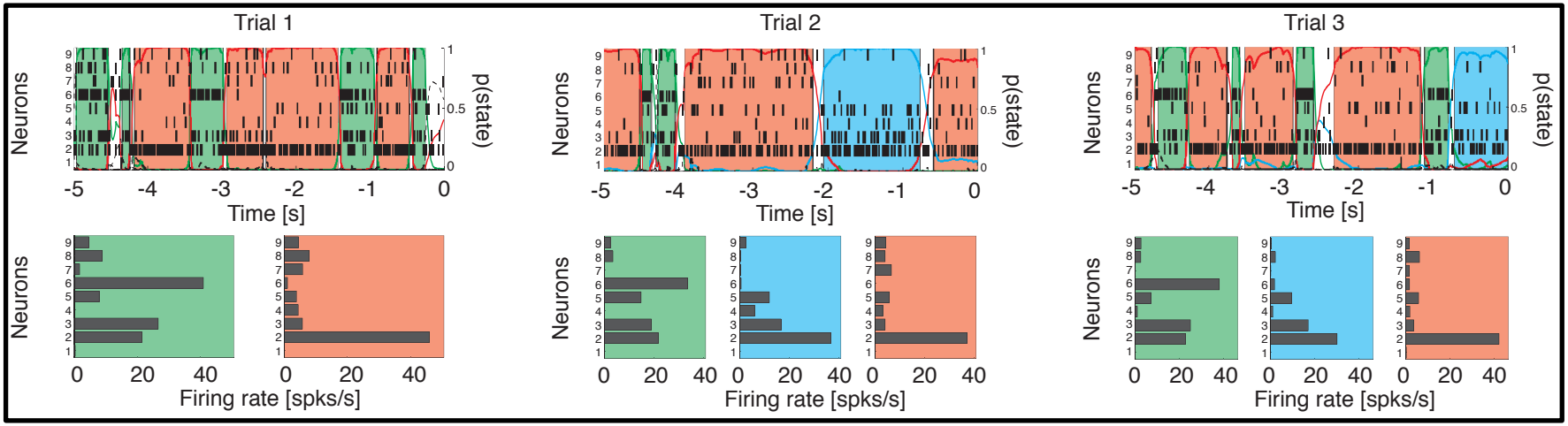
[Mazzucato et al., 2015]

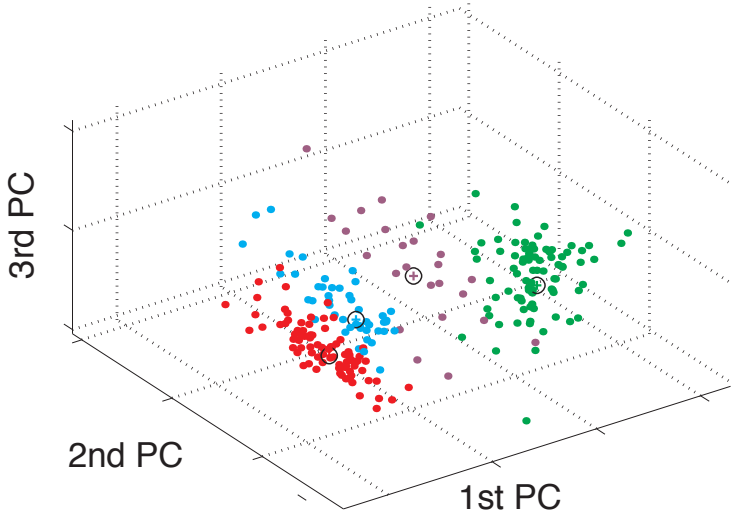
Ongoing activity



Mazzucato et al., 2015

Ongoing activity

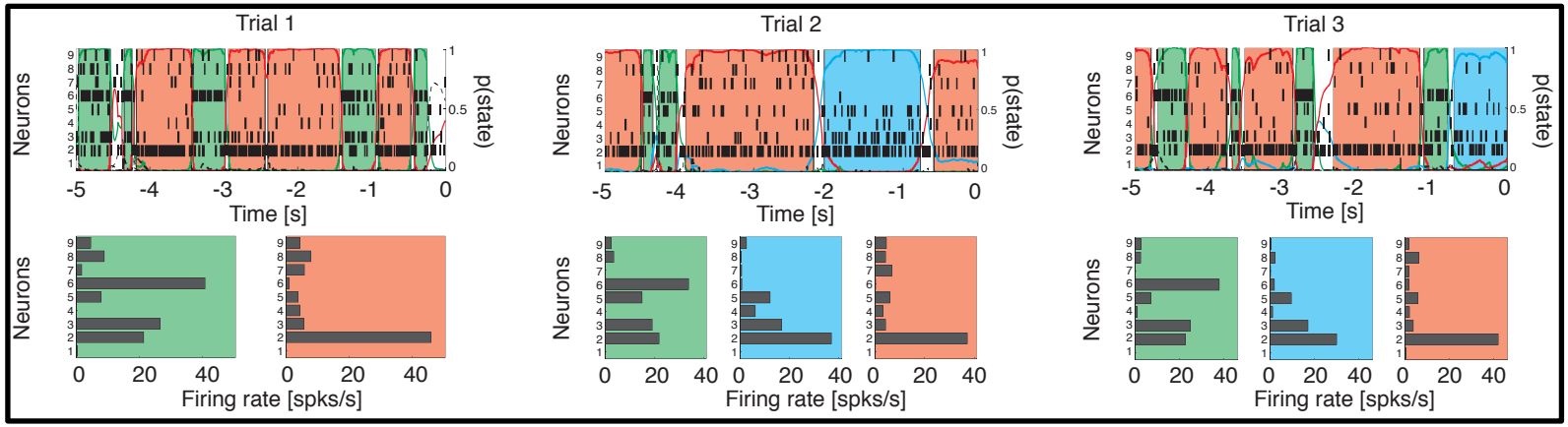




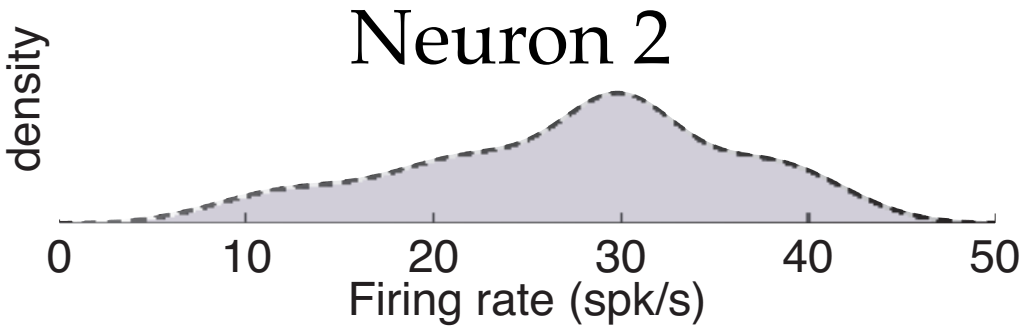
States cluster in PCA space

Mazzucato et al., 2015

Ongoing activity: multistability

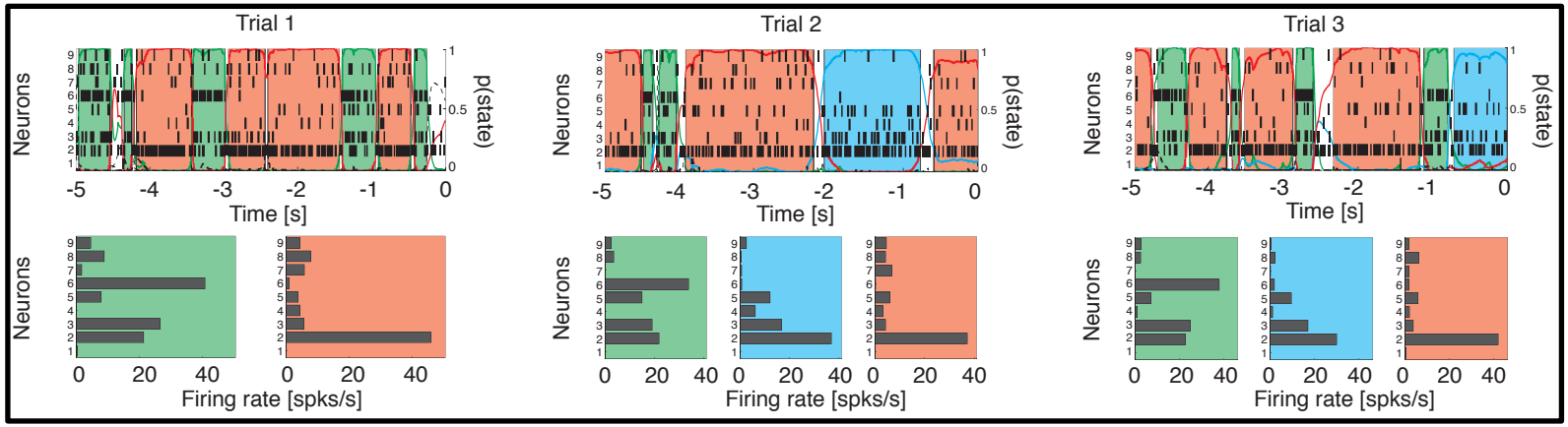


Single neuron firing rate distribution

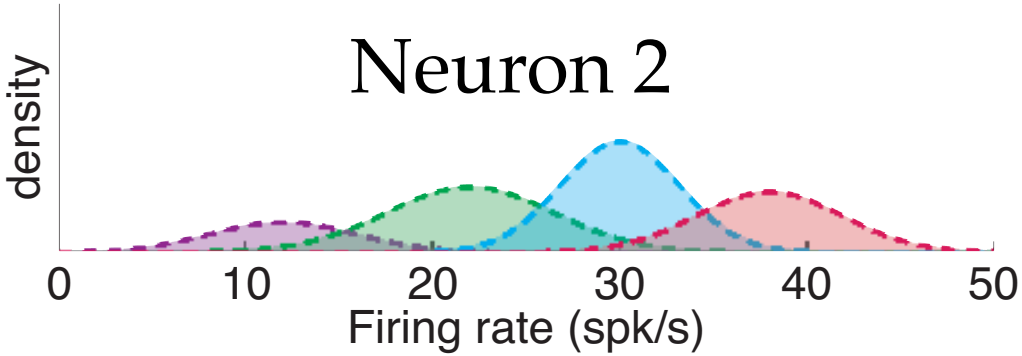


Mazzucato et al., 2015

Ongoing activity: multistability



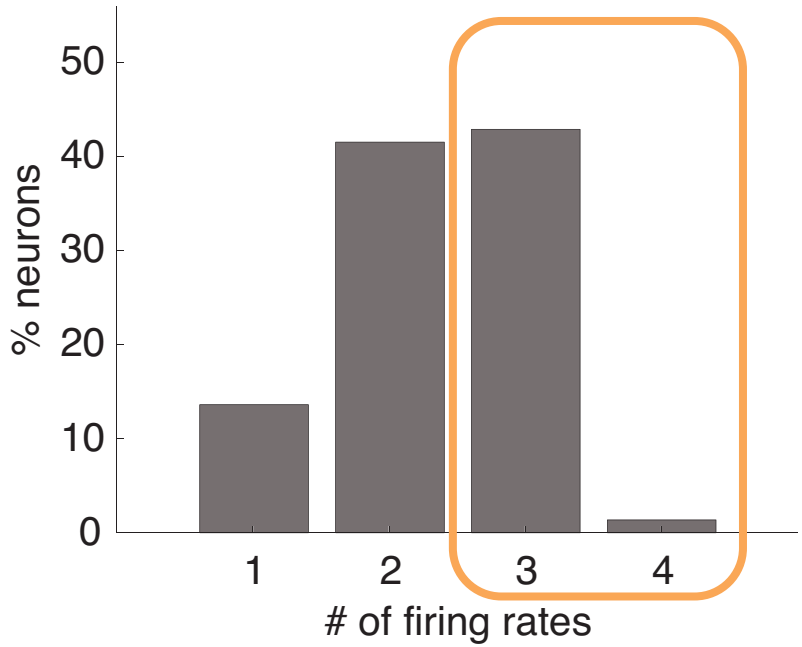
4 different firing rates across states: “multistable”



Mazzucato et al., 2015

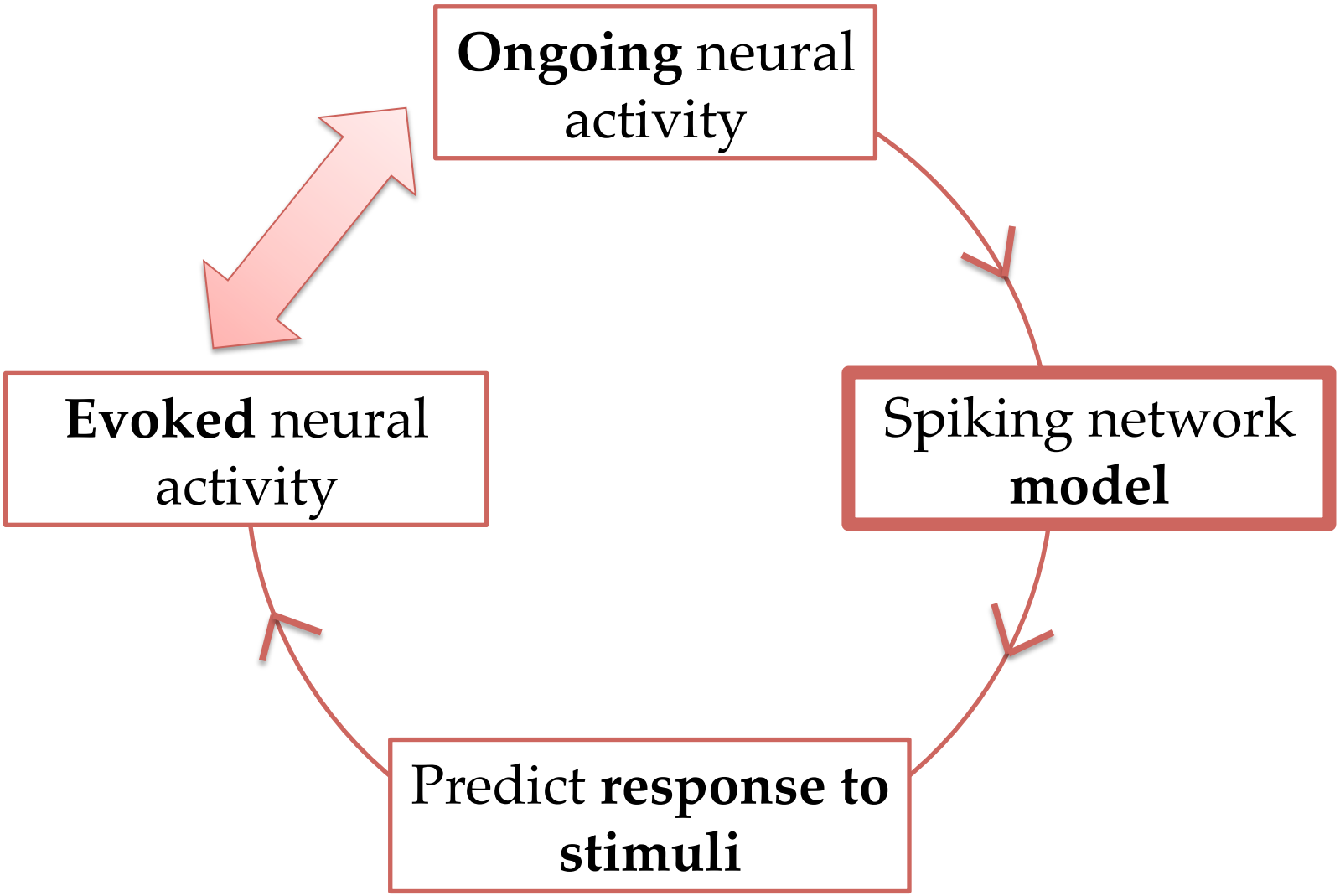
Ongoing activity: multistability

42% of neurons have 3 or more firing rates across states



Mazzucato et al., 2015

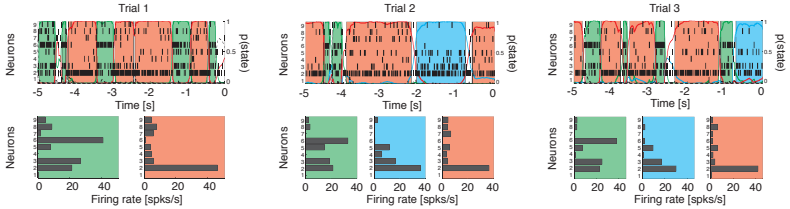
A unifying approach



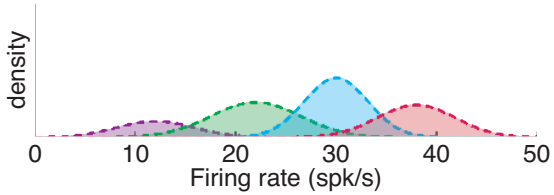
Ongoing activity: Model

A model that captures ongoing activity:

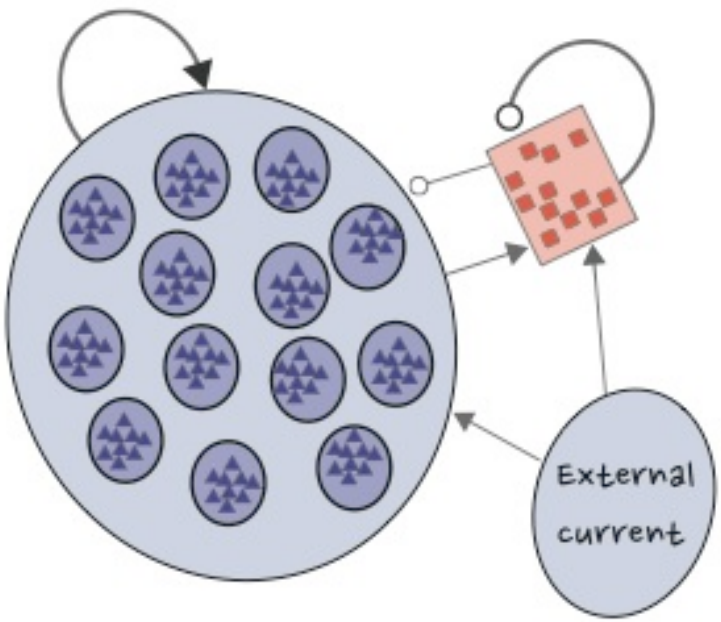
1. State sequences



2. Single neuron multistability



Ongoing activity: Model

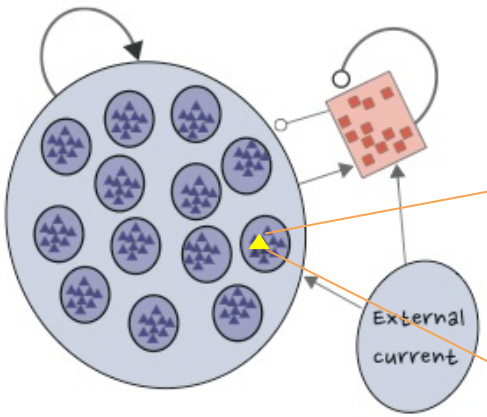


$N_E = 4000$

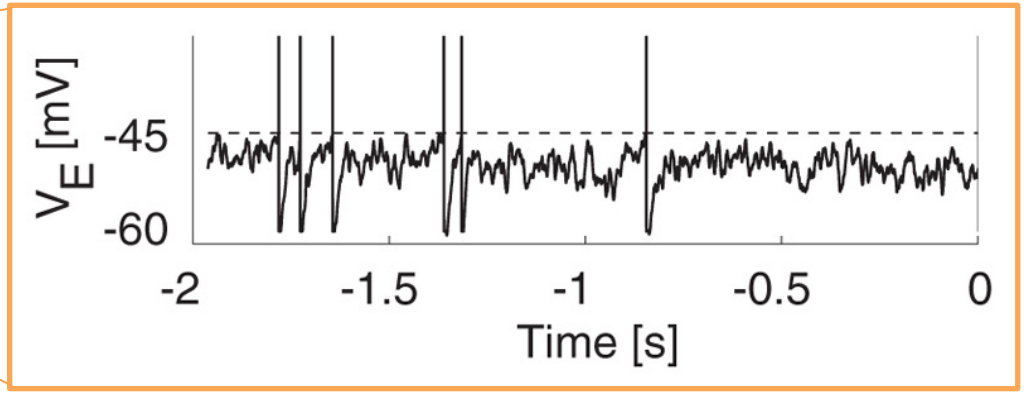
$N_I = 1000$

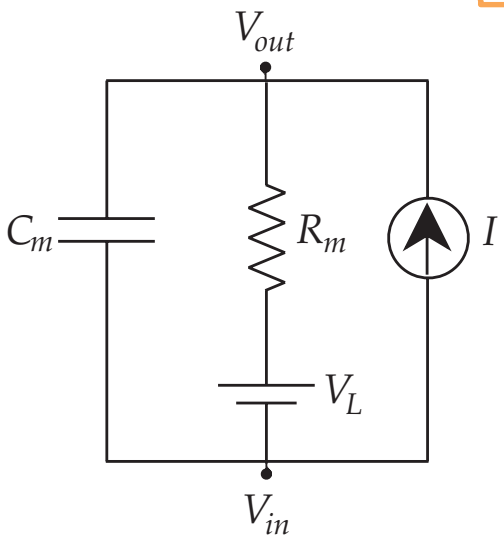
30 clusters

Ongoing activity: Model



Leaky integrate-and-fire neurons:



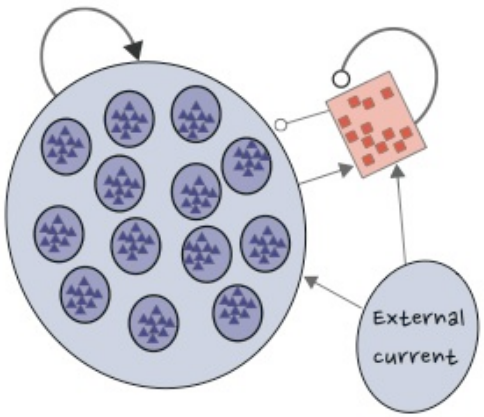


$$\tau_m \frac{dV}{dt} = -V + \tau_m(I_{rec} + I_{ext} + I_{stim})$$

Membrane constant: $\tau_m = R_m C_m$

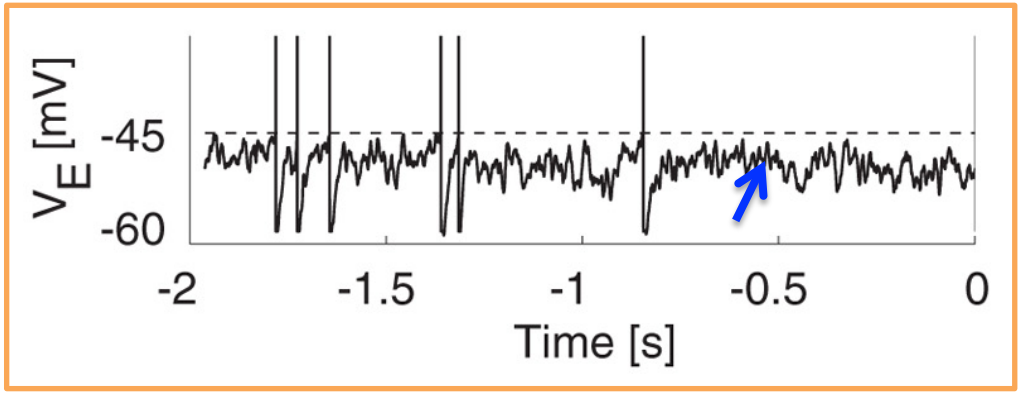
Resting potential: $V_L = 0$

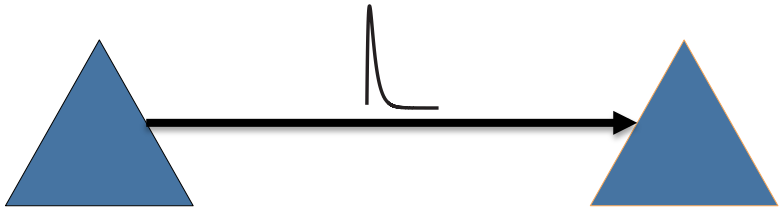
Ongoing activity: Model



N_E
N_I
clusters

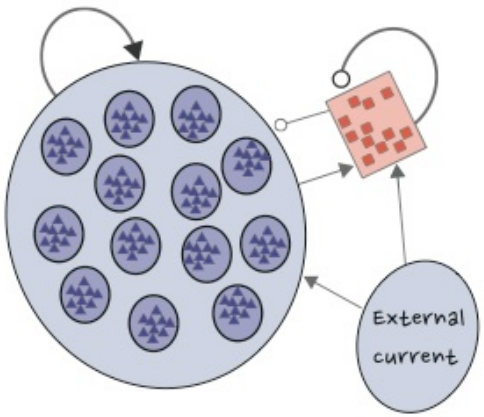
Leaky integrate-and-fire neurons:





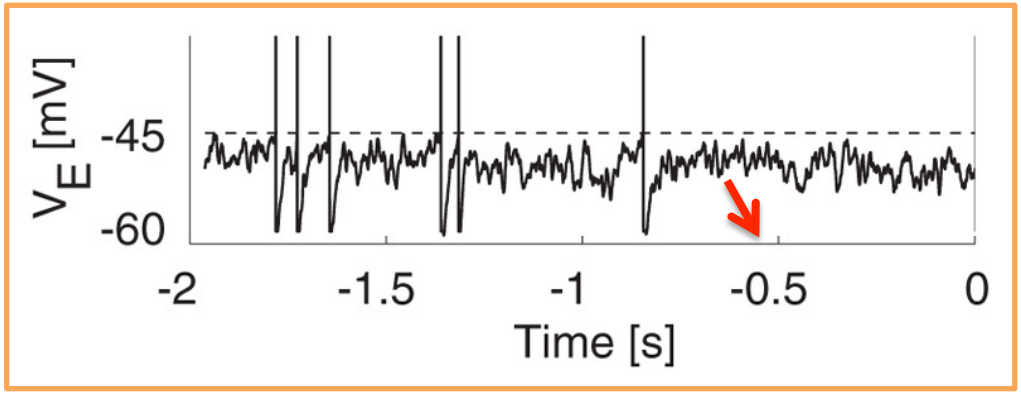
Excitatory
neuron

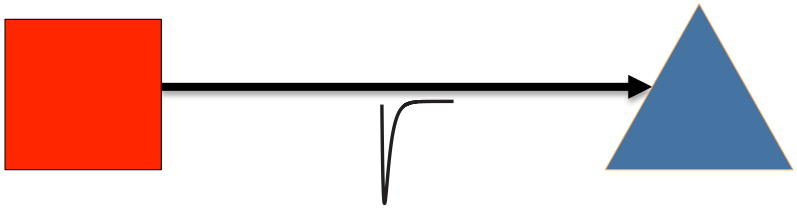
Ongoing activity: Model



N_E
N_I
clusters

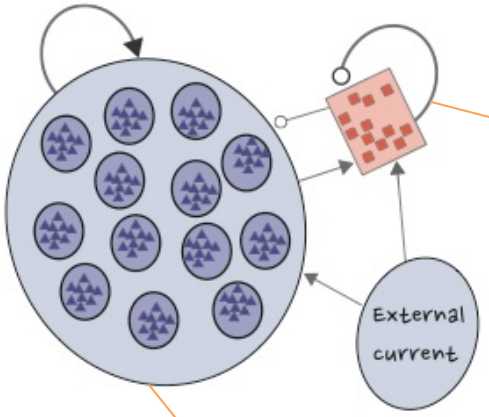
Leaky integrate-and-fire neurons:



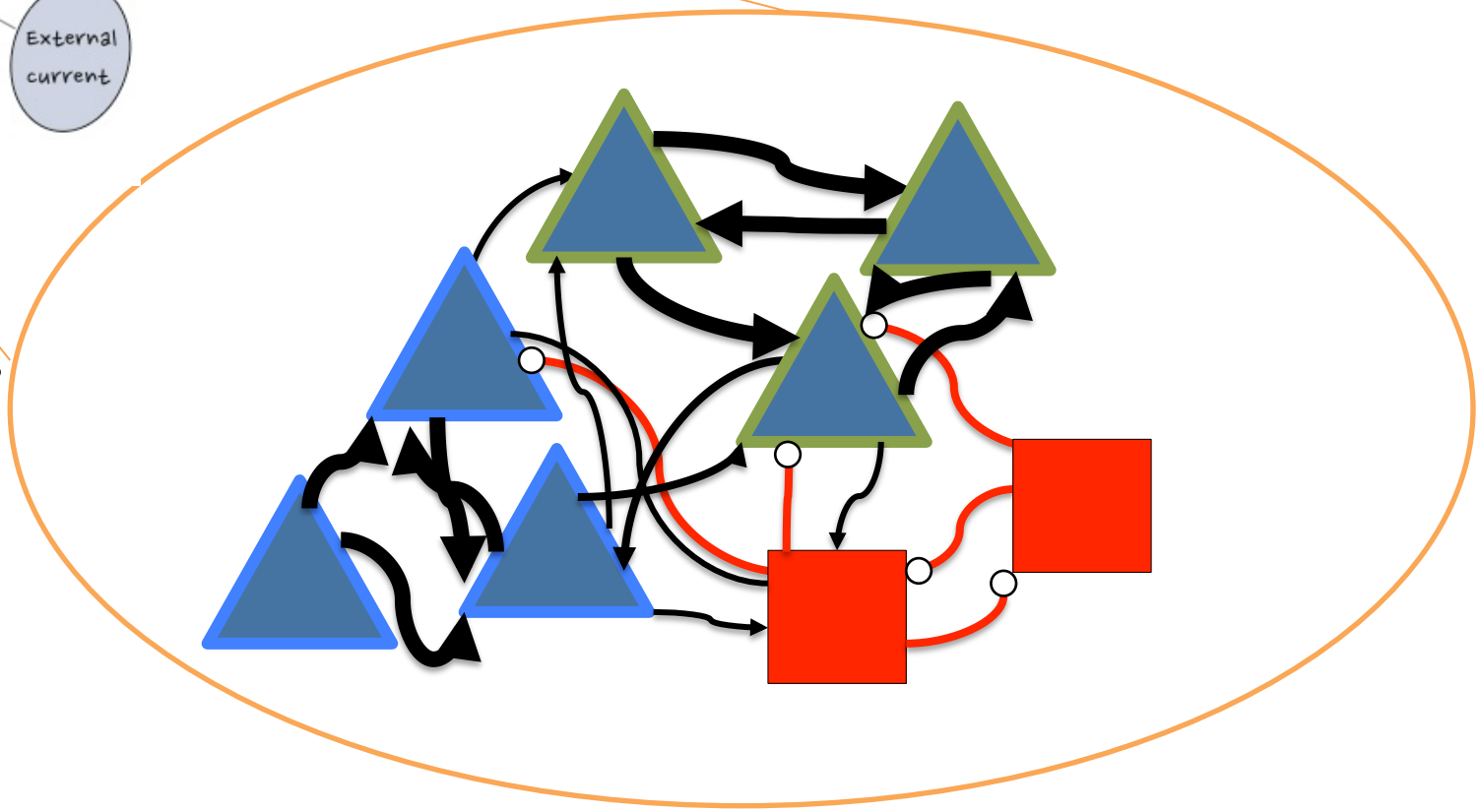


Inhibitory
neuron

Clustered network



Cluster: stronger recurrent synaptic weights

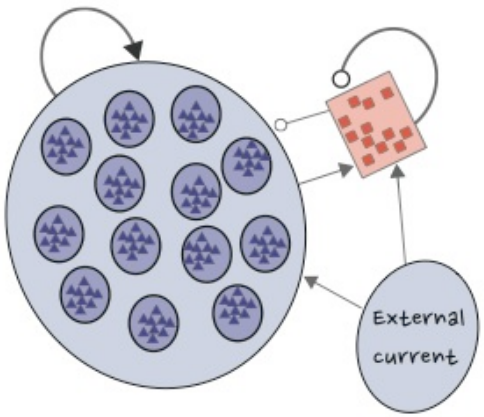


N_E

N_I

clusters

Ongoing activity: Model

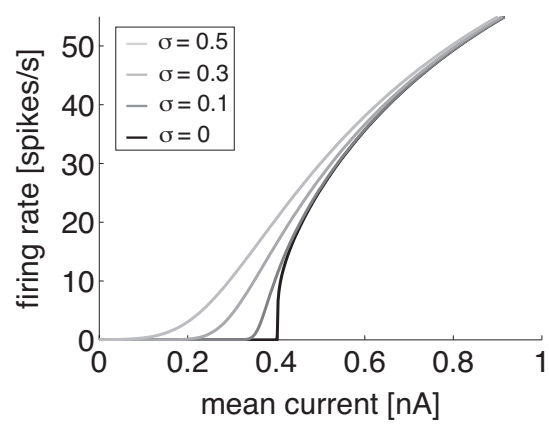


N_E
N_I
clusters

Mean field theory

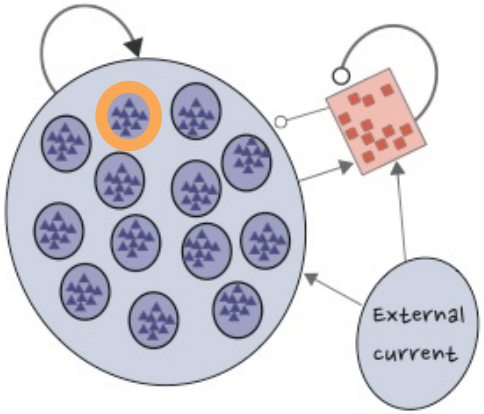
$$\nu_\alpha = F\left(I_\alpha(\vec{\nu}), \sigma_\alpha^2(\vec{\nu})\right)$$

Current-to-rate
response function



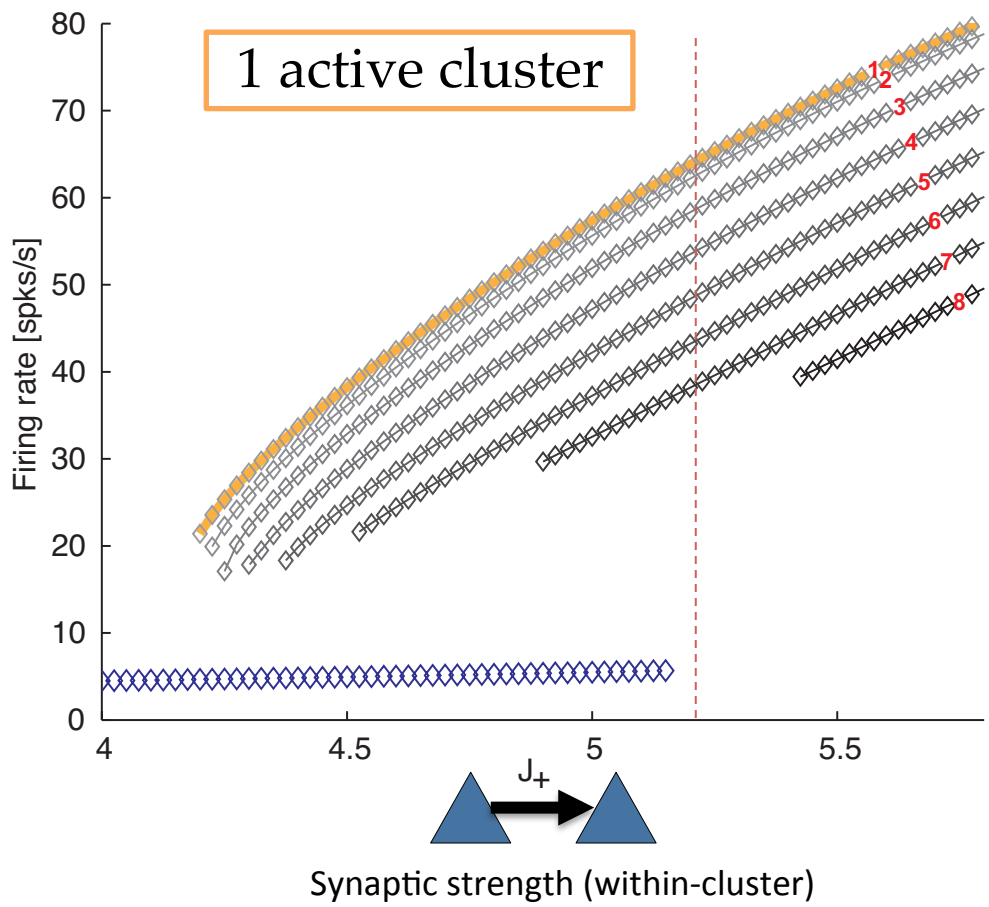
La Camera et al., 2008

Ongoing activity: Model



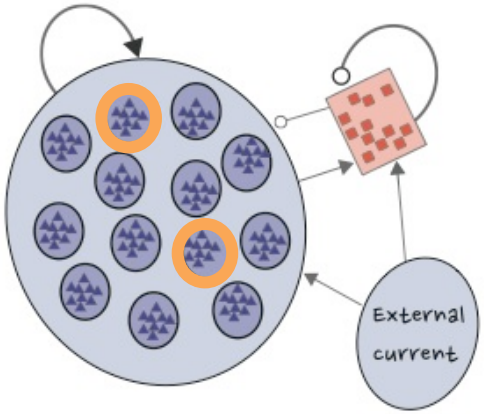
N_E
N_I
clusters

Mean field theory: stable states



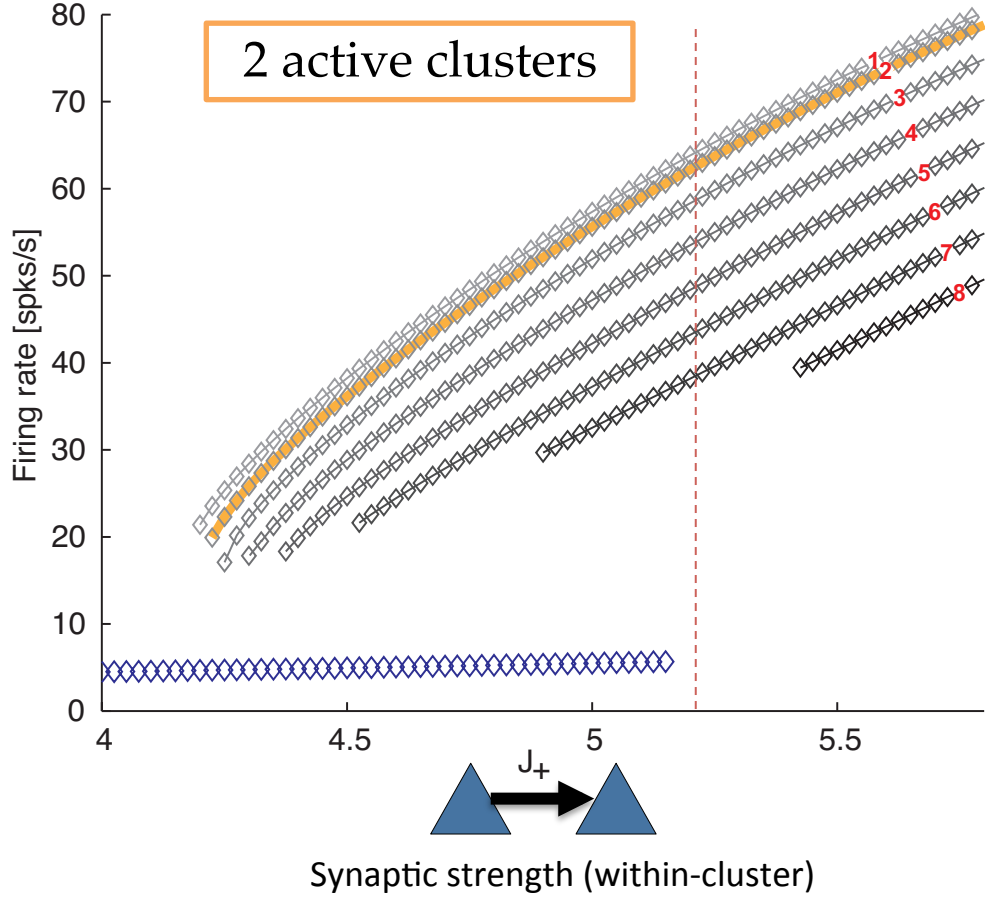
Mazzucato et al., 2015

Ongoing activity: Model



N_E
N_I
clusters

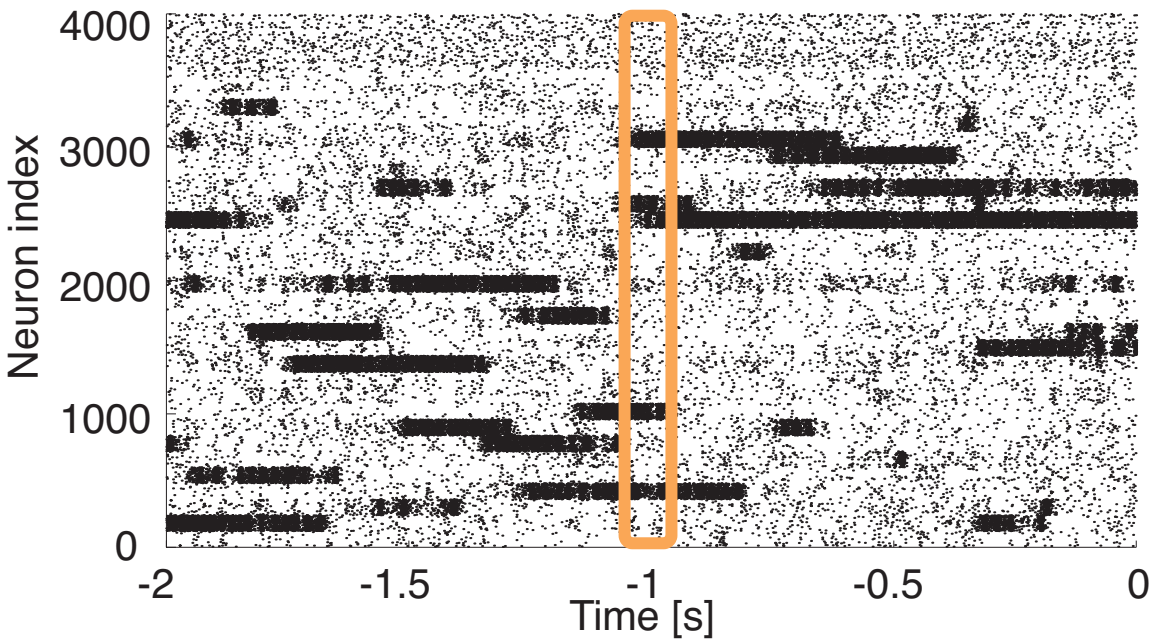
Firing rates depend on the # of active clusters

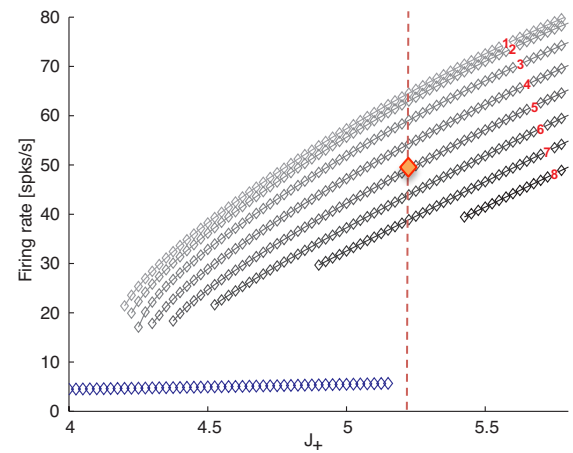


Mazzucato et al., 2015

Ongoing activity: Model

Simulation



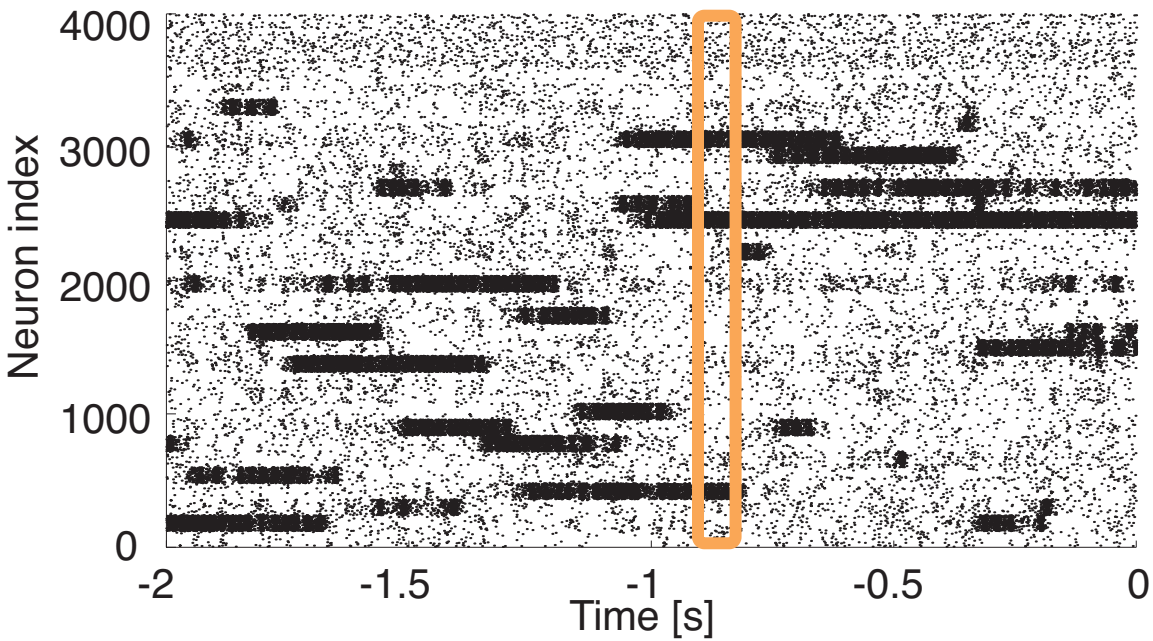


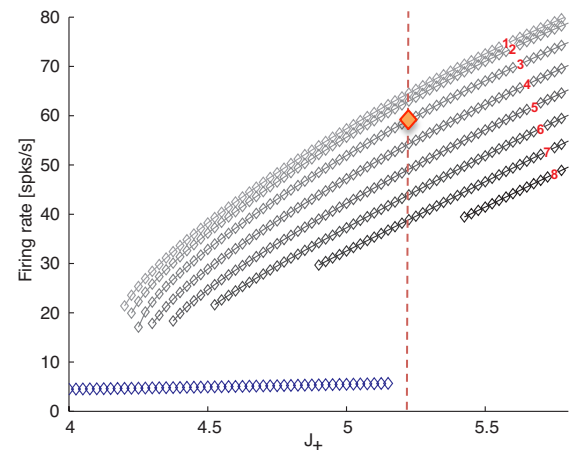
5 active clusters

Mazzucato et al., 2015

Ongoing activity: Model

Simulation

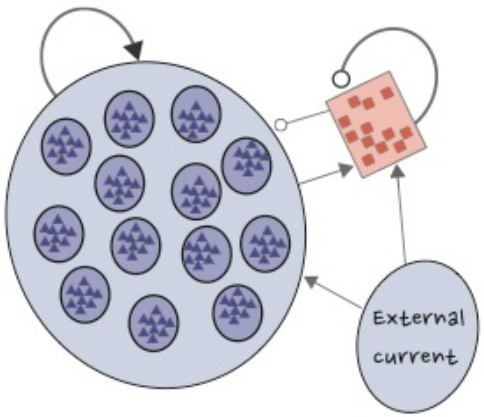




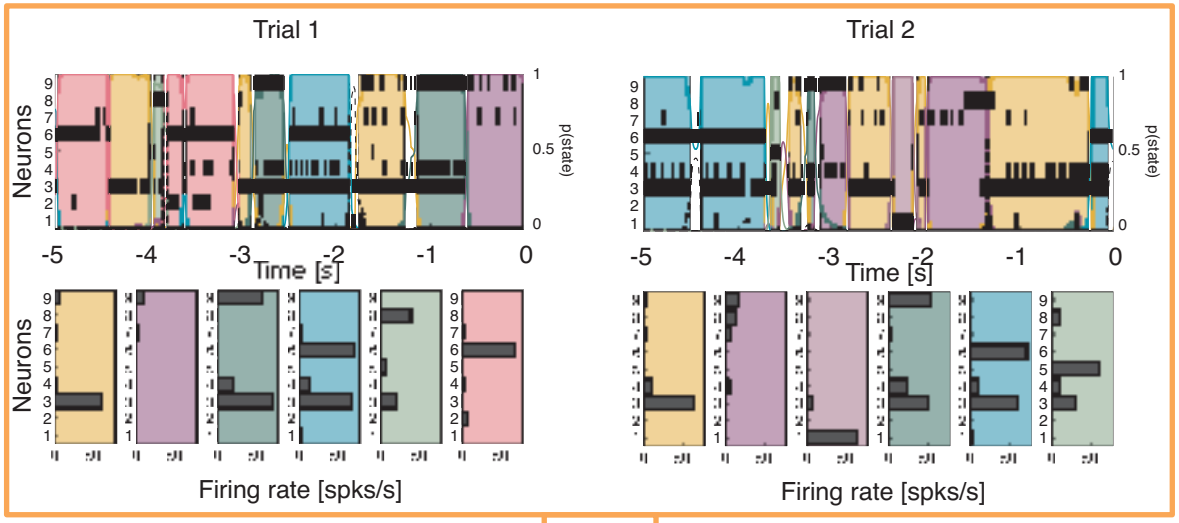
3 active clusters

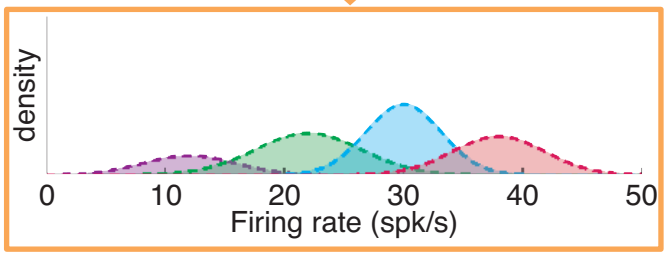
Mazzucato et al., 2015

Ongoing activity: Model



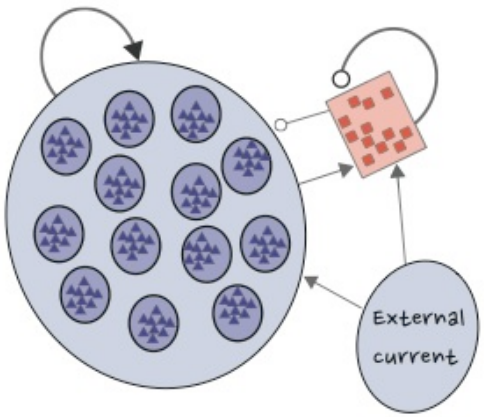
N_E
N_I
30 clusters





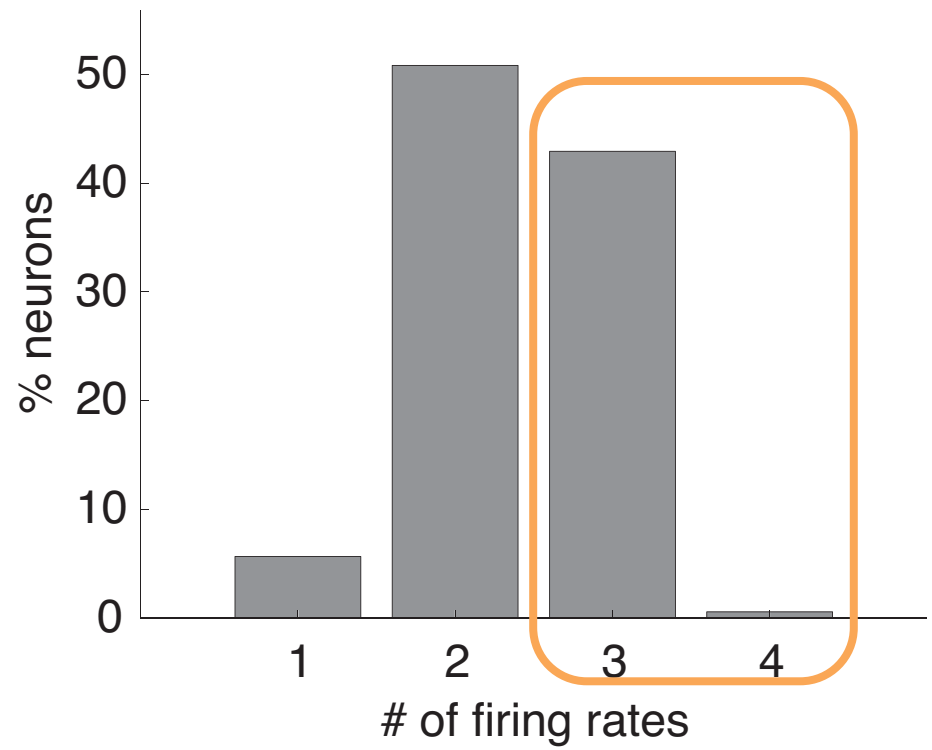
Mazzucato et al., 2015

Ongoing activity: Model



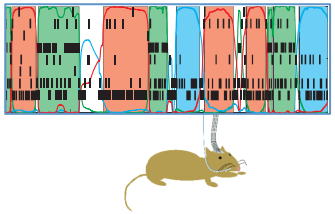
N_E
N_I
30 clusters

44% of neurons have 3 or more firing rates across states

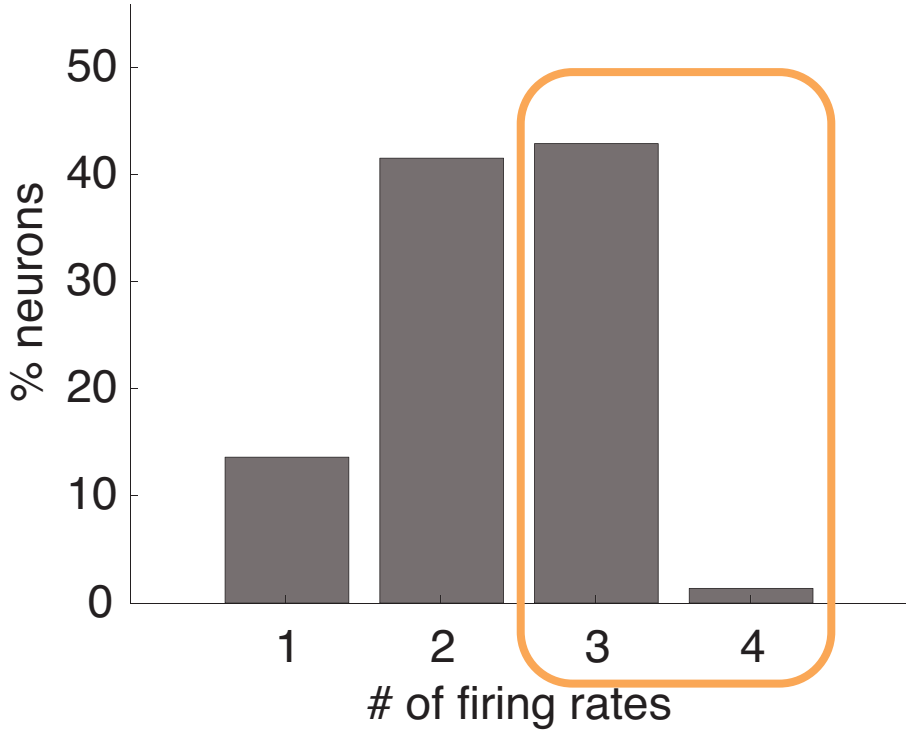


Mazzucato et al., 2015

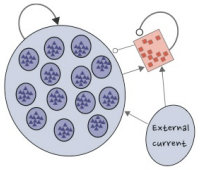
Ongoing activity: Multistability



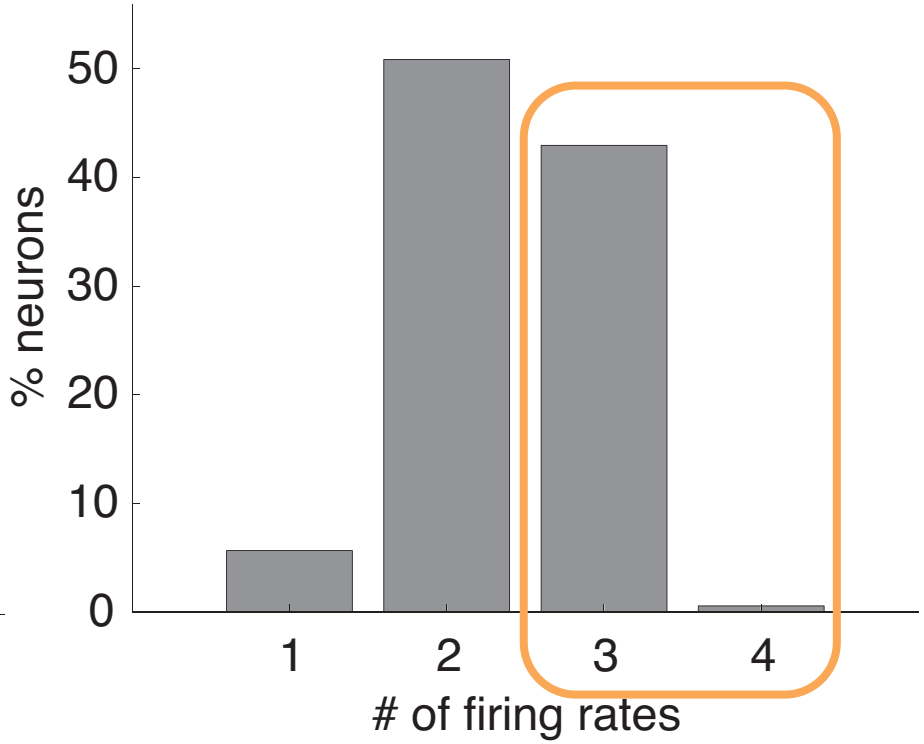
42%



Data



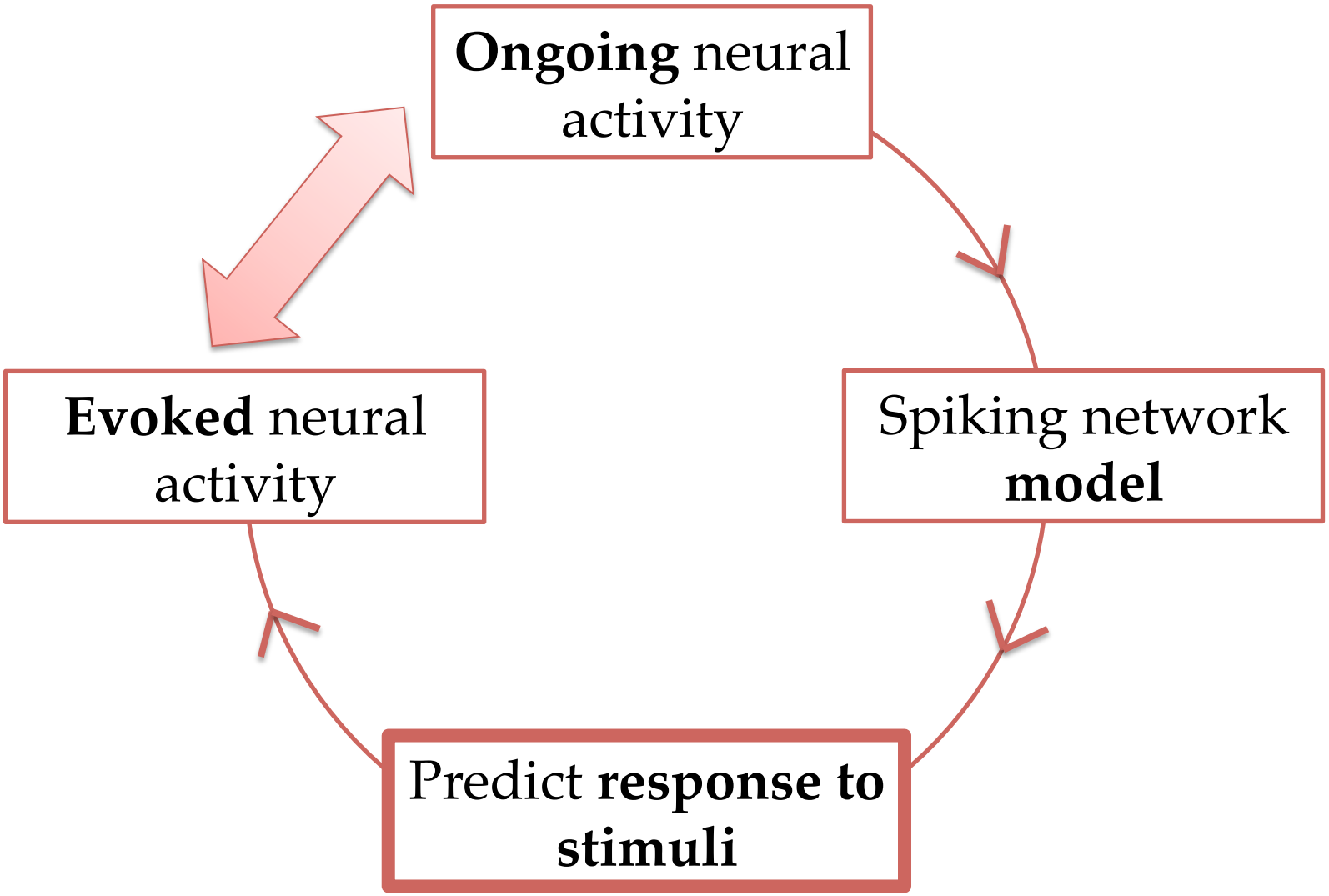
44%



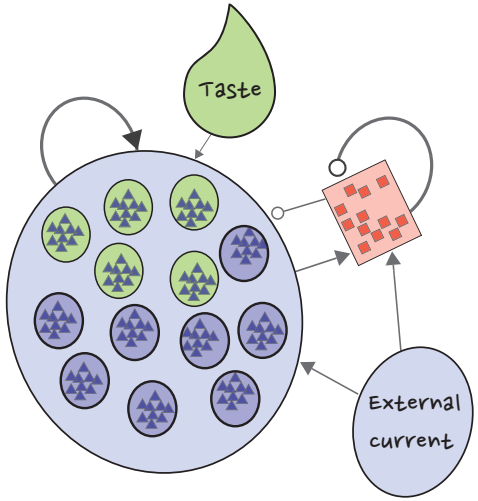
Model

Mazzucato et al., 2015

A unifying approach

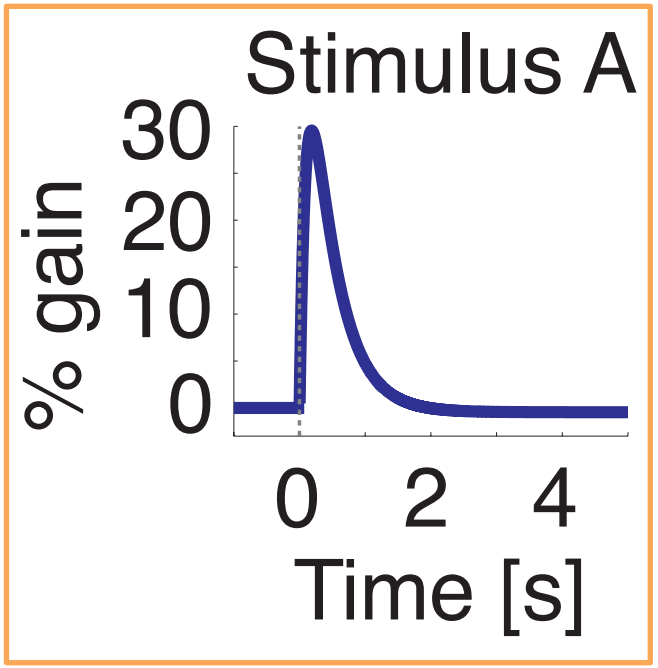


Evoked activity: Model



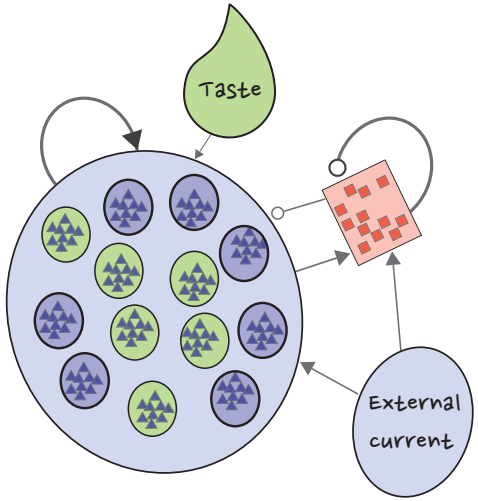
N_E
N_I
30 clusters

Deliver 1 out of 4 sensory stimuli:



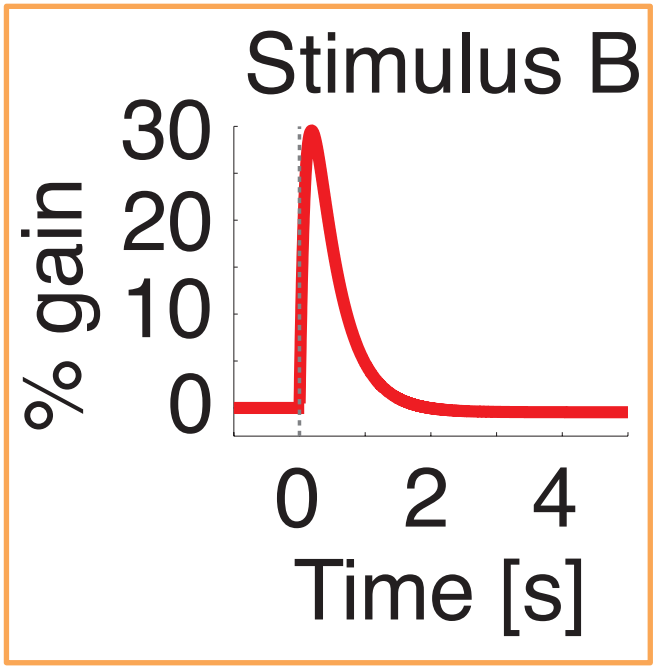
Mazzucato et al., 2015

Evoked activity: Model



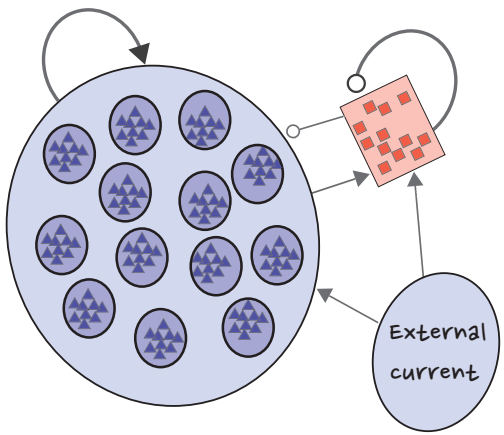
N_E
N_I
30 clusters

Deliver 1 out of 4 sensory stimuli:



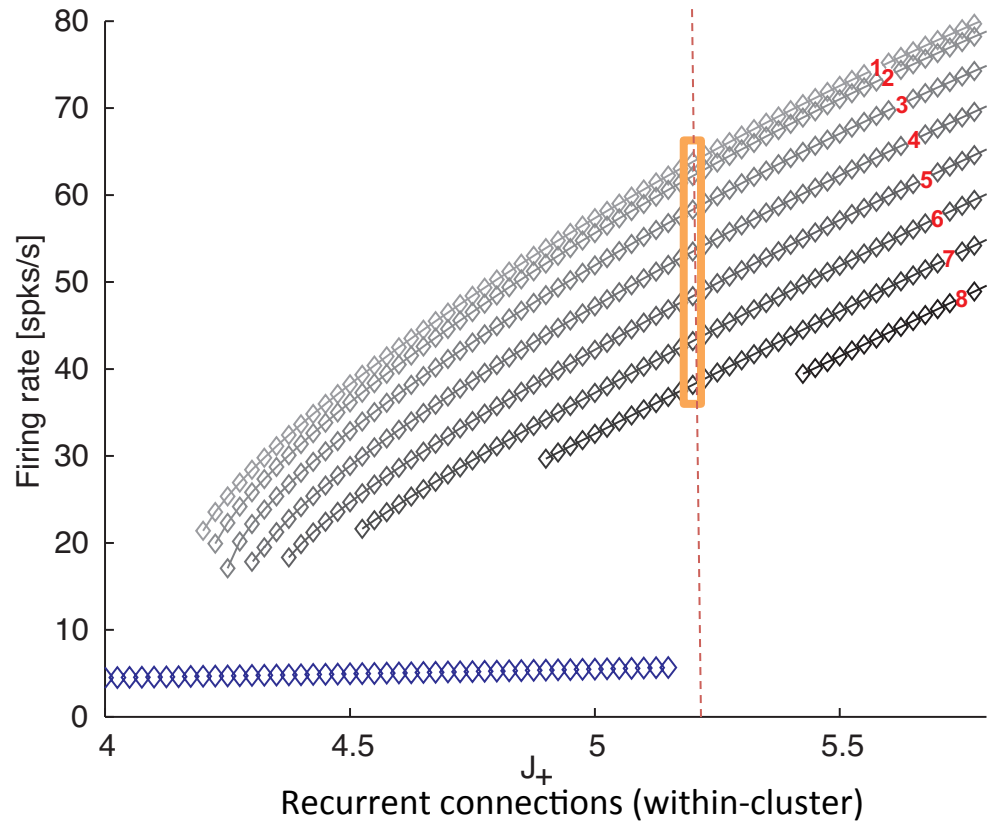
Mazzucato et al., 2015

Ongoing activity: Model



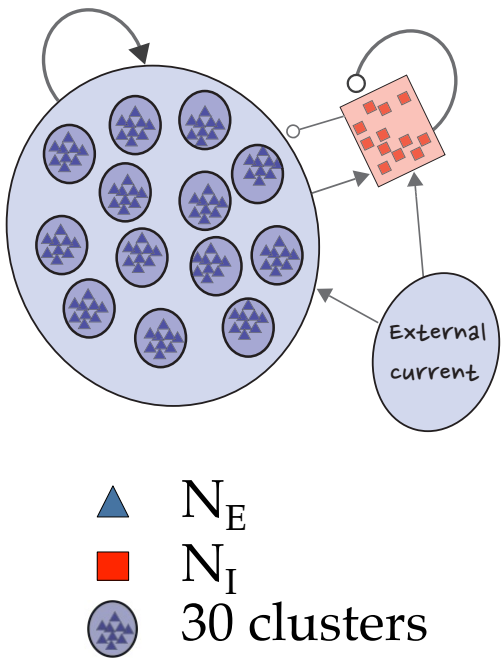
N_E
N_I
30 clusters

Stable states (no stimulus)

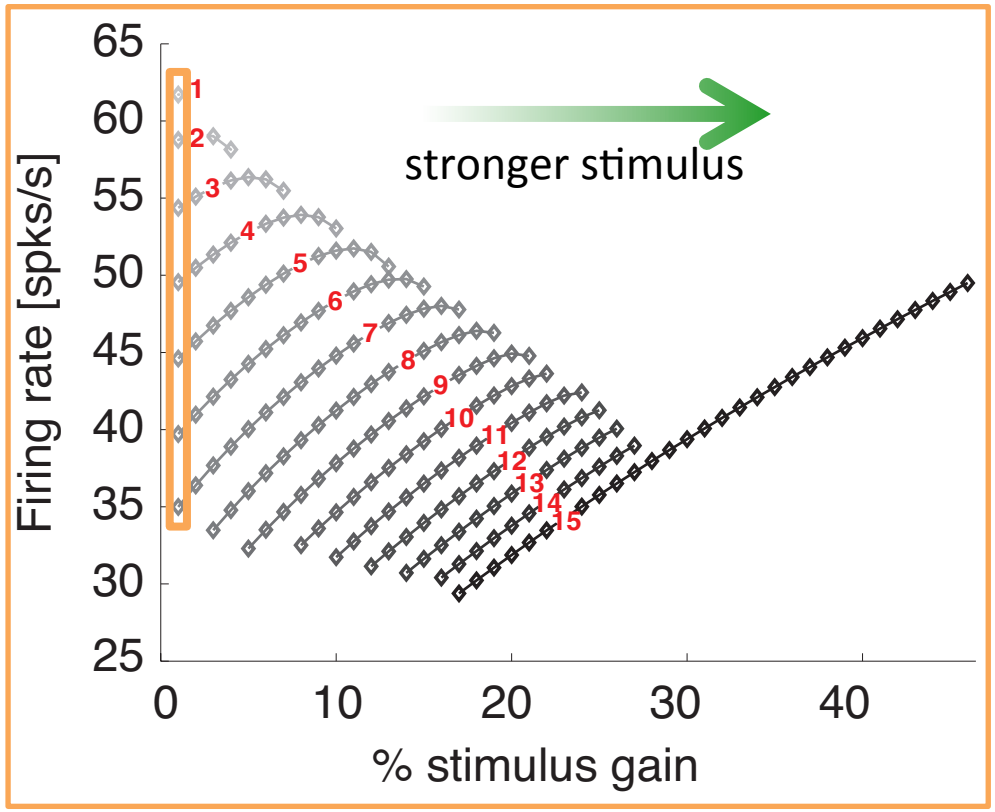


Mazzucato et al., 2015

Evoked activity: Model

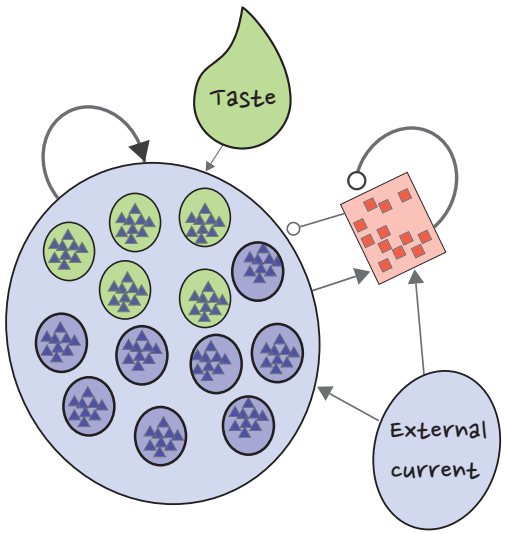


Stable states (dial up stimulus)



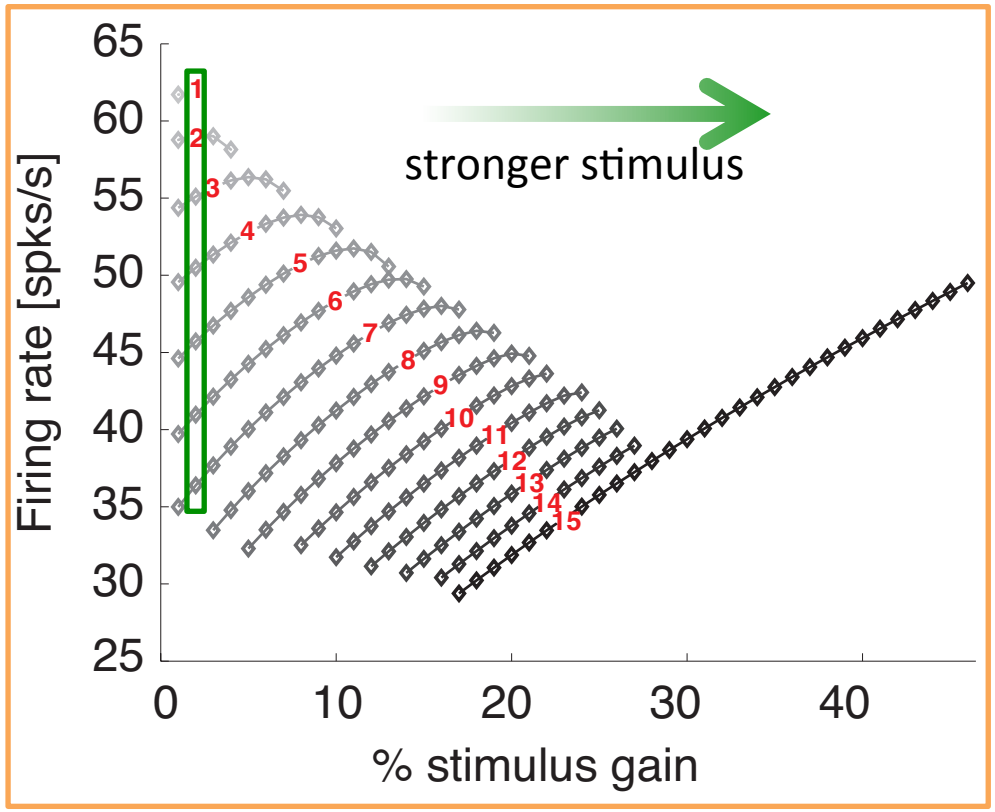
Mazzucato et al., 2015

Evoked activity: Model



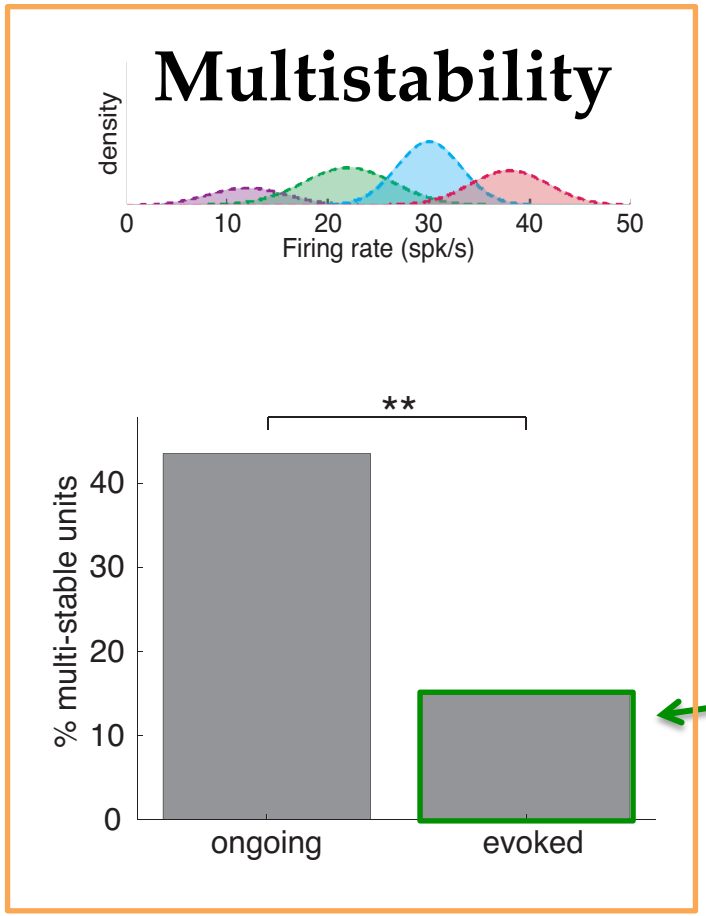
N_E
N_I
30 clusters

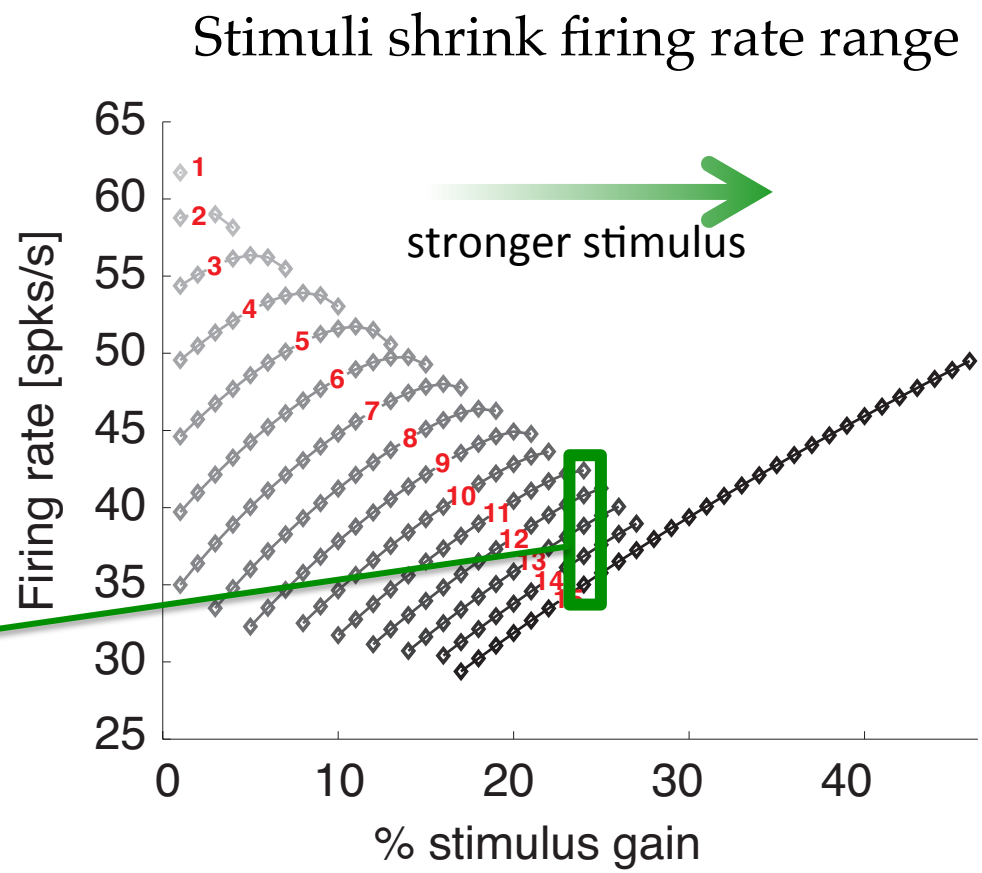
Stable states (dial up stimulus)



Mazzucato et al., 2015

Evoked activity: Model

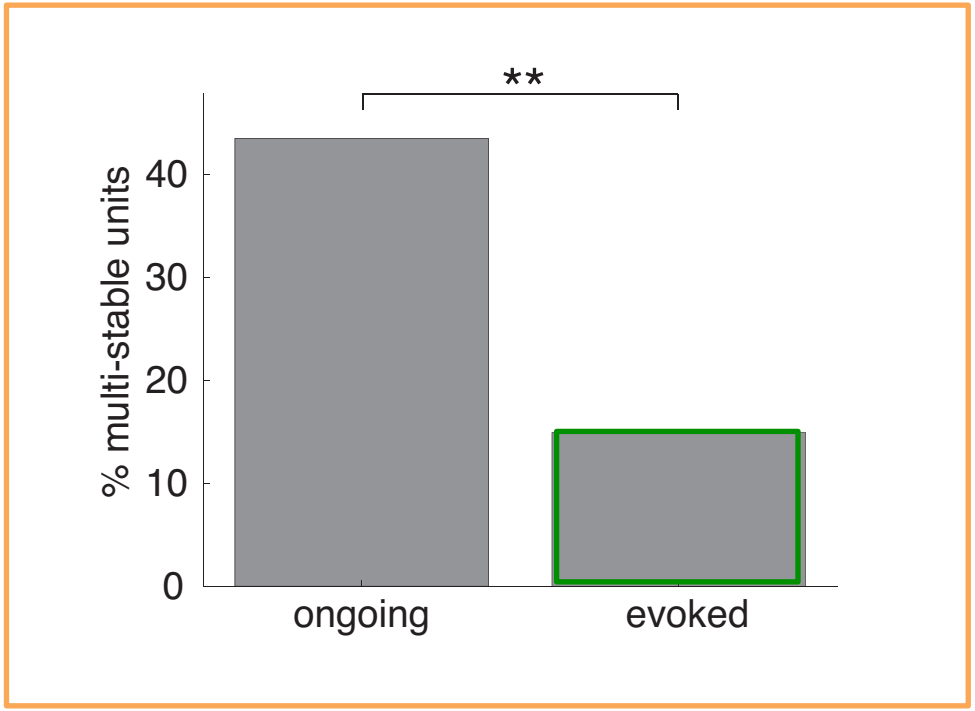




Mazzucato et al., 2015

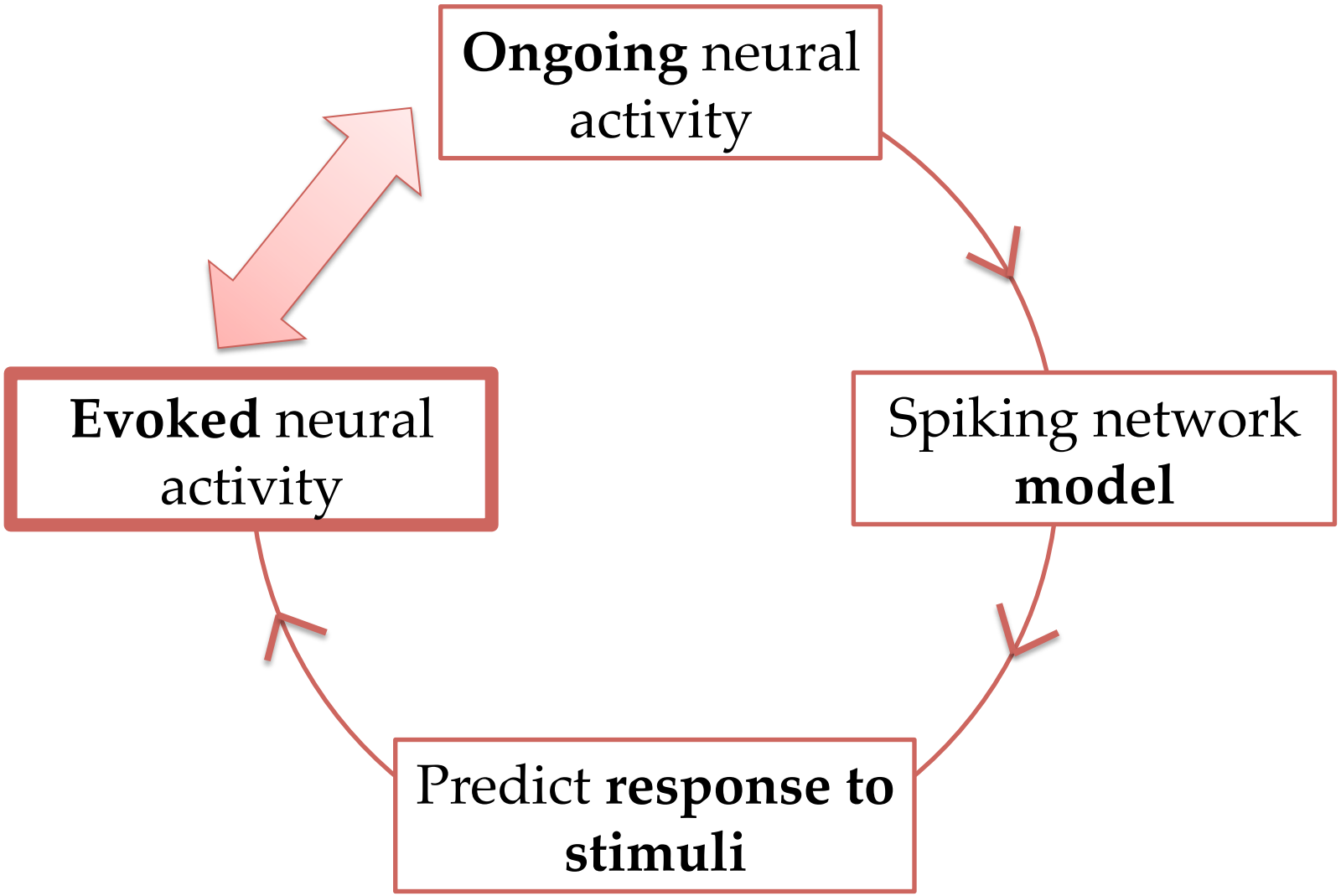
Stimuli reduce multistability

Model prediction

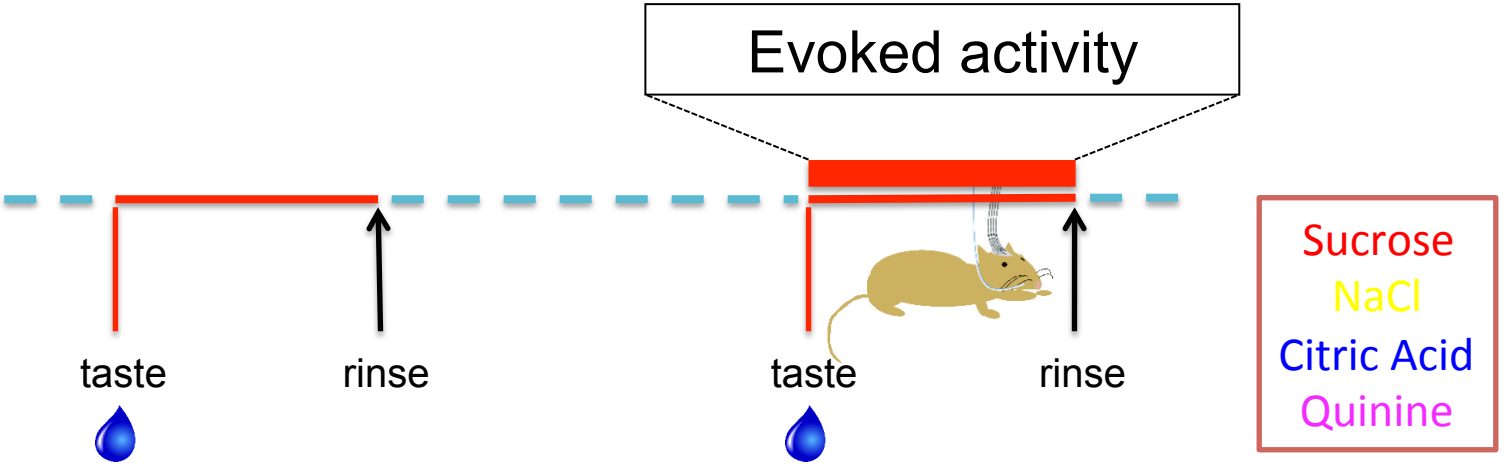


Mazzucato et al., 2015

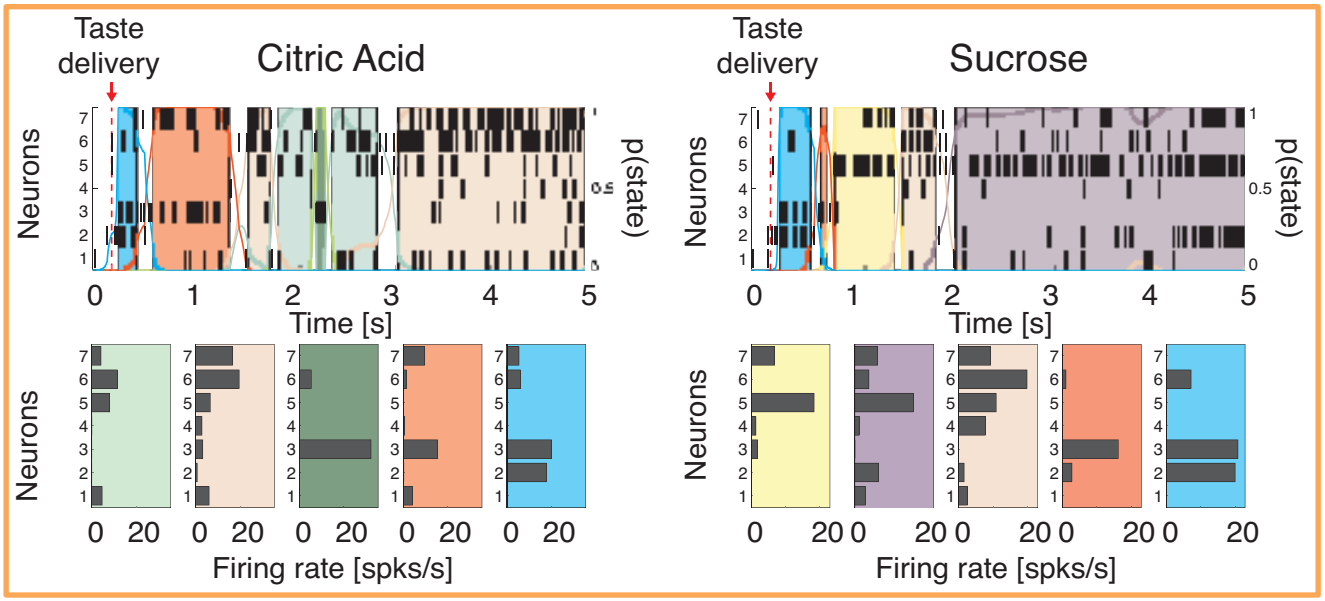
A unifying approach

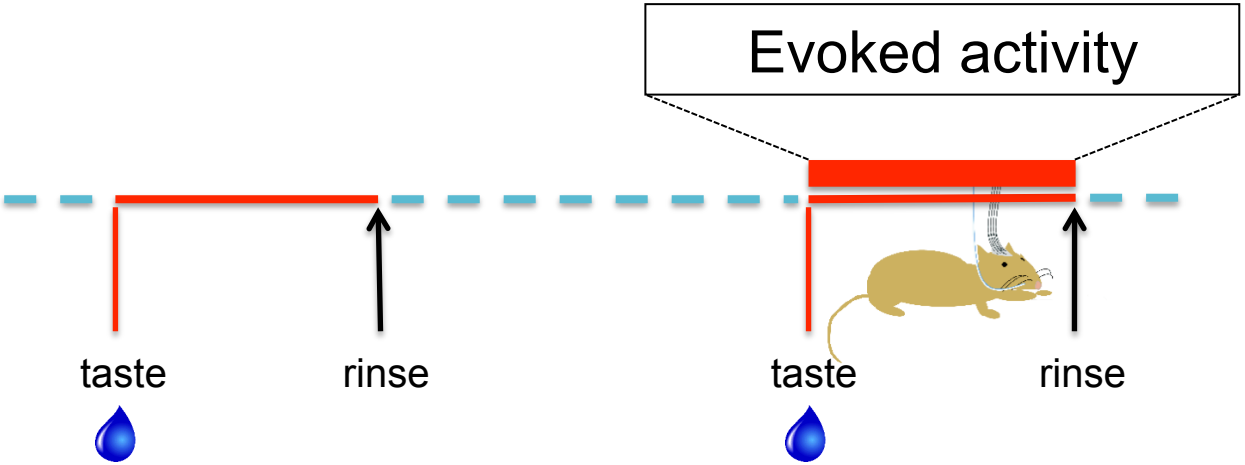


Experiment

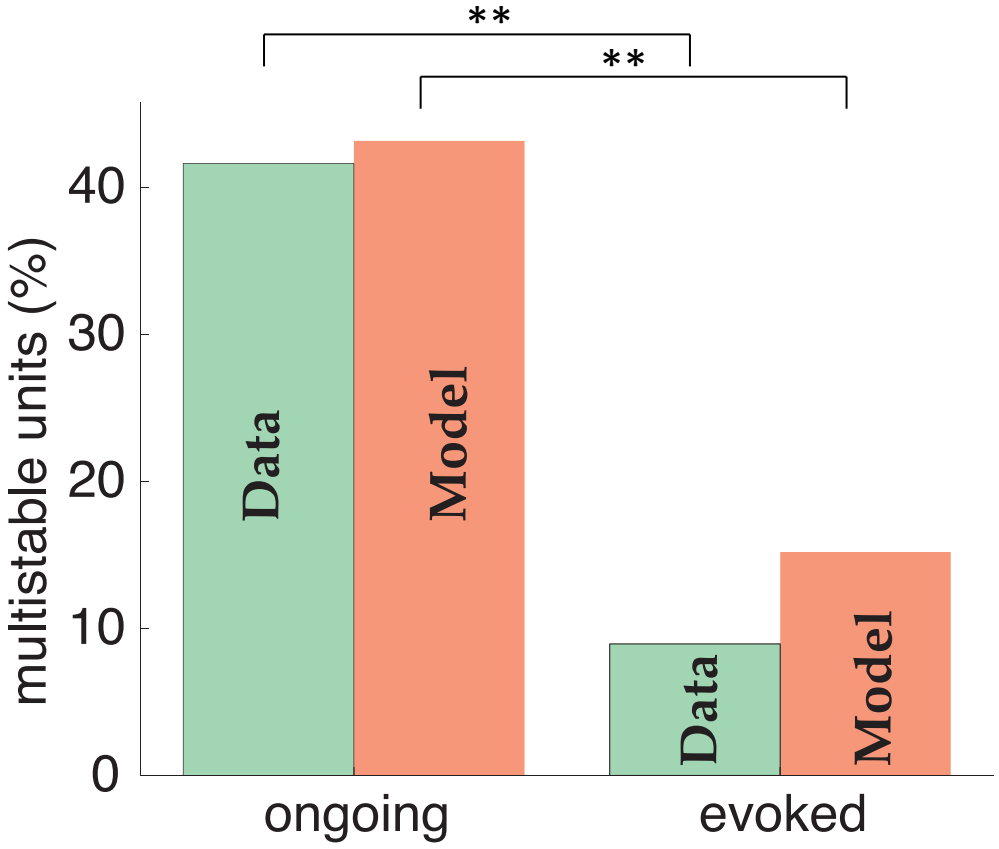

Evoked activity
taste
rinse
taste
rinse
Sucrose
NaCl
Citric Acid
Quinine

Taste-evoked activity



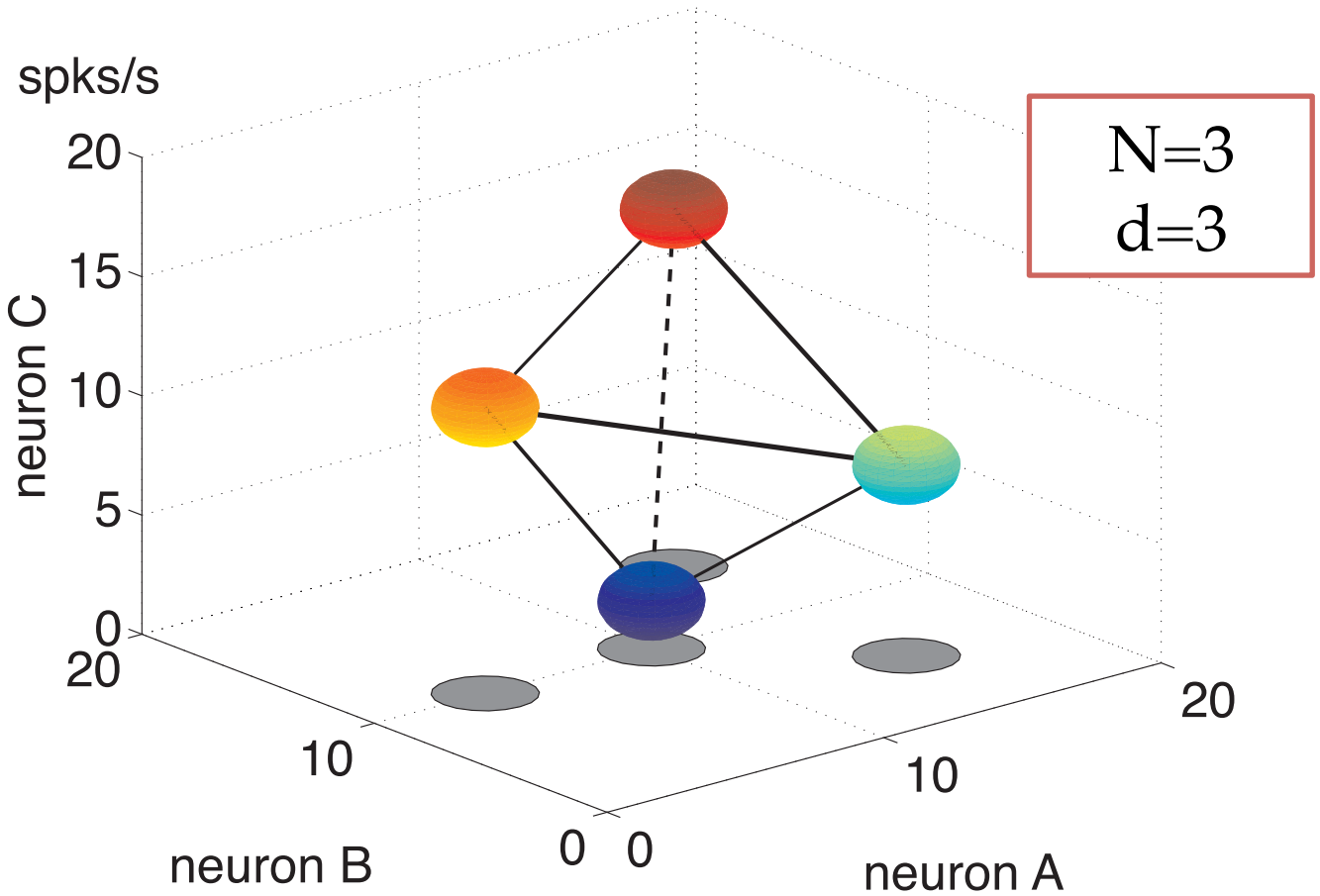


Stimuli reduce multistability



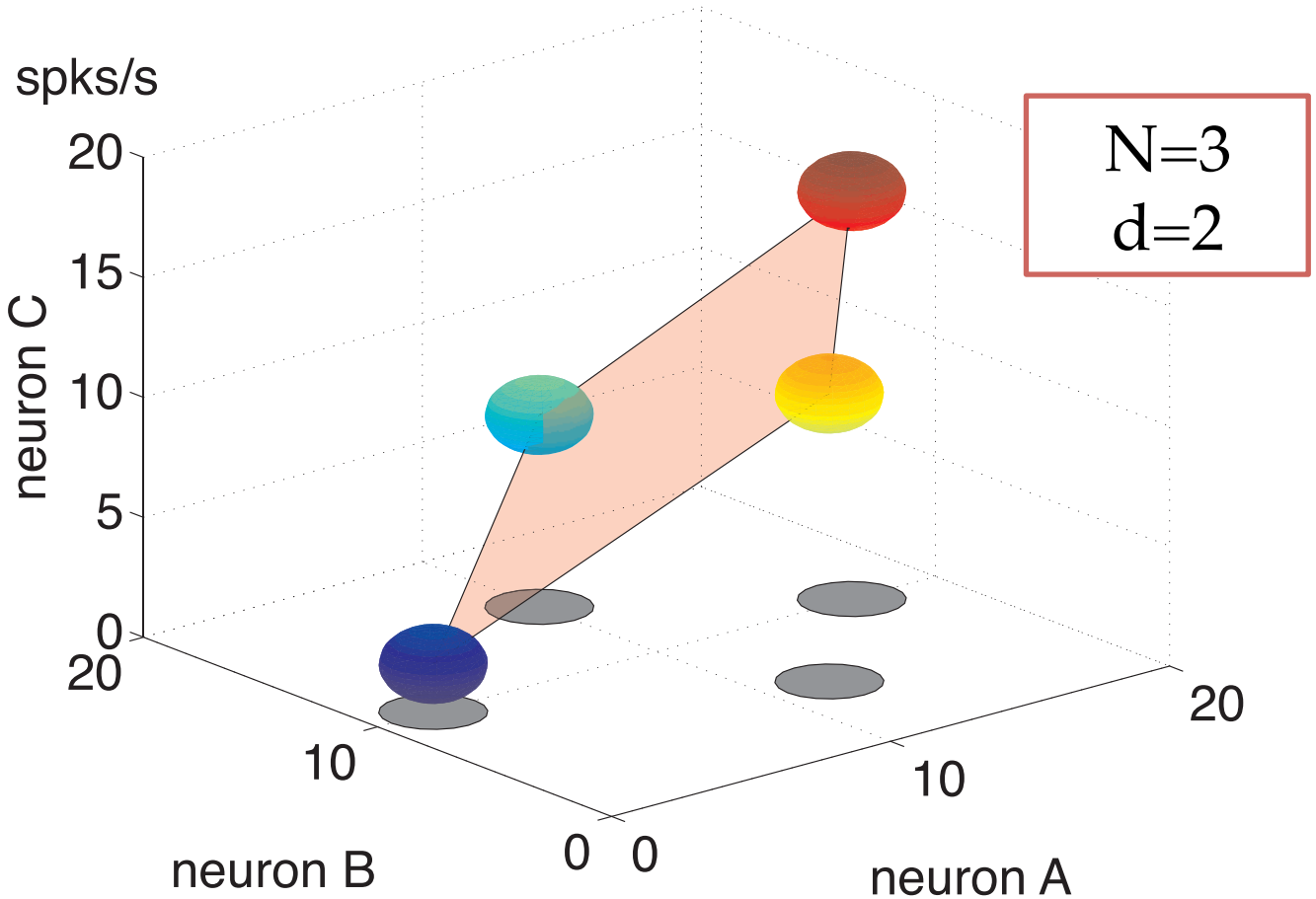
Mazzucato et al., 2015

Neural dimensionality



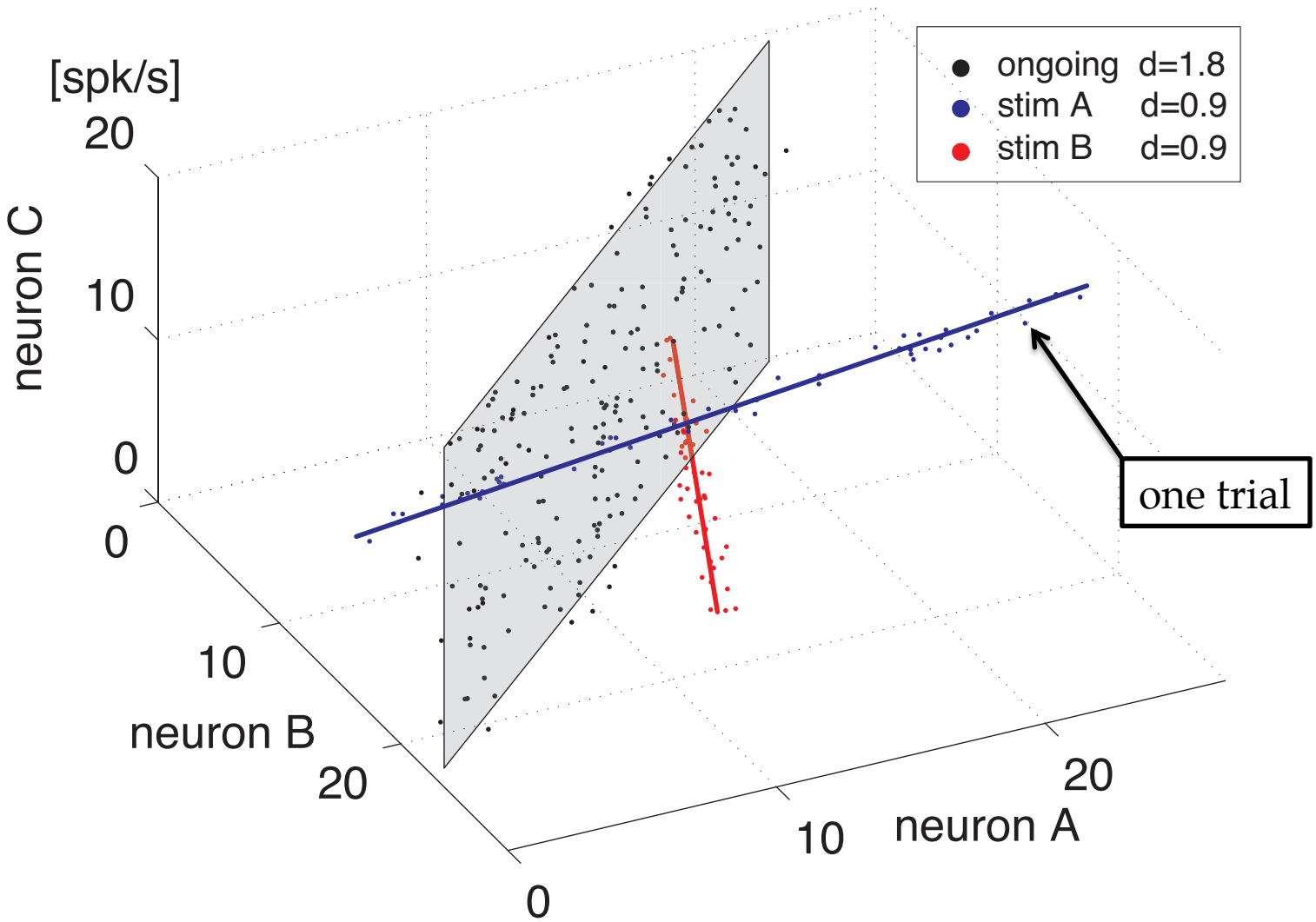
Mazzucato et al., 2016

Neural dimensionality



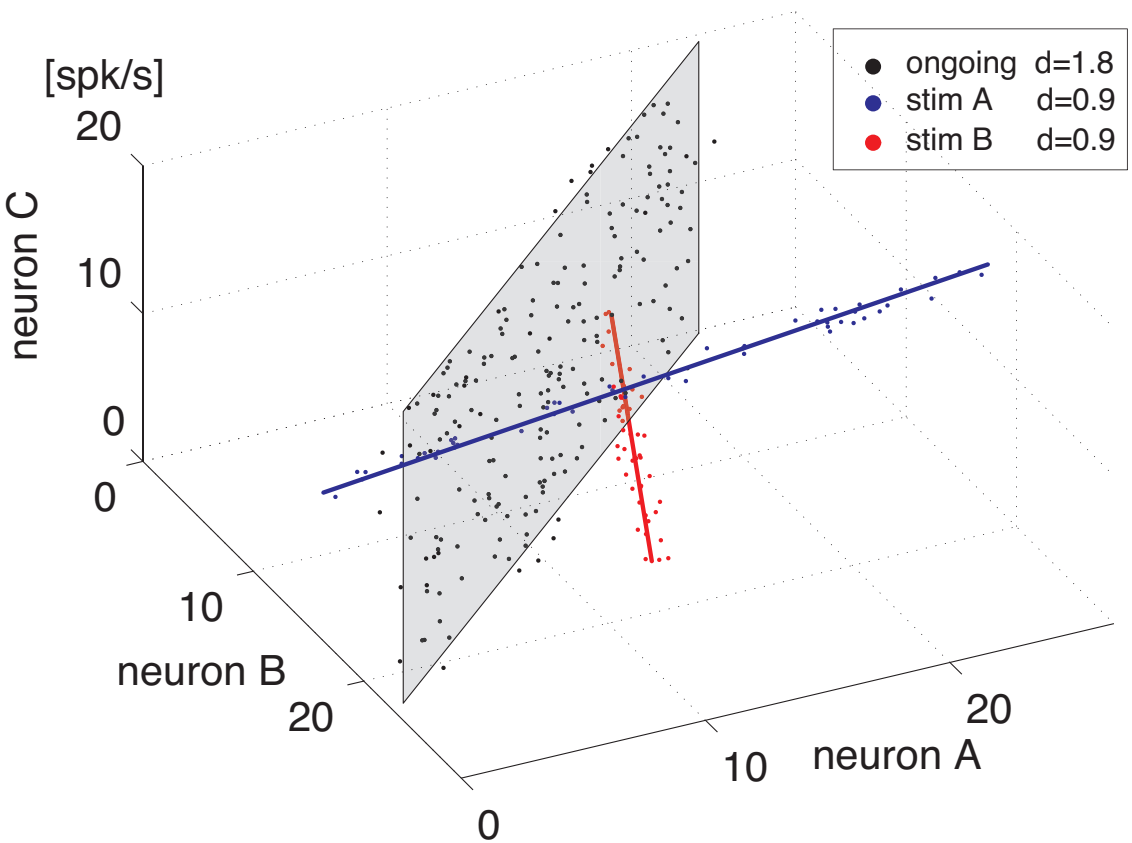
Mazzucato et al., 2016

Neural dimensionality



Mazzucato et al., 2016

Neural dimensionality



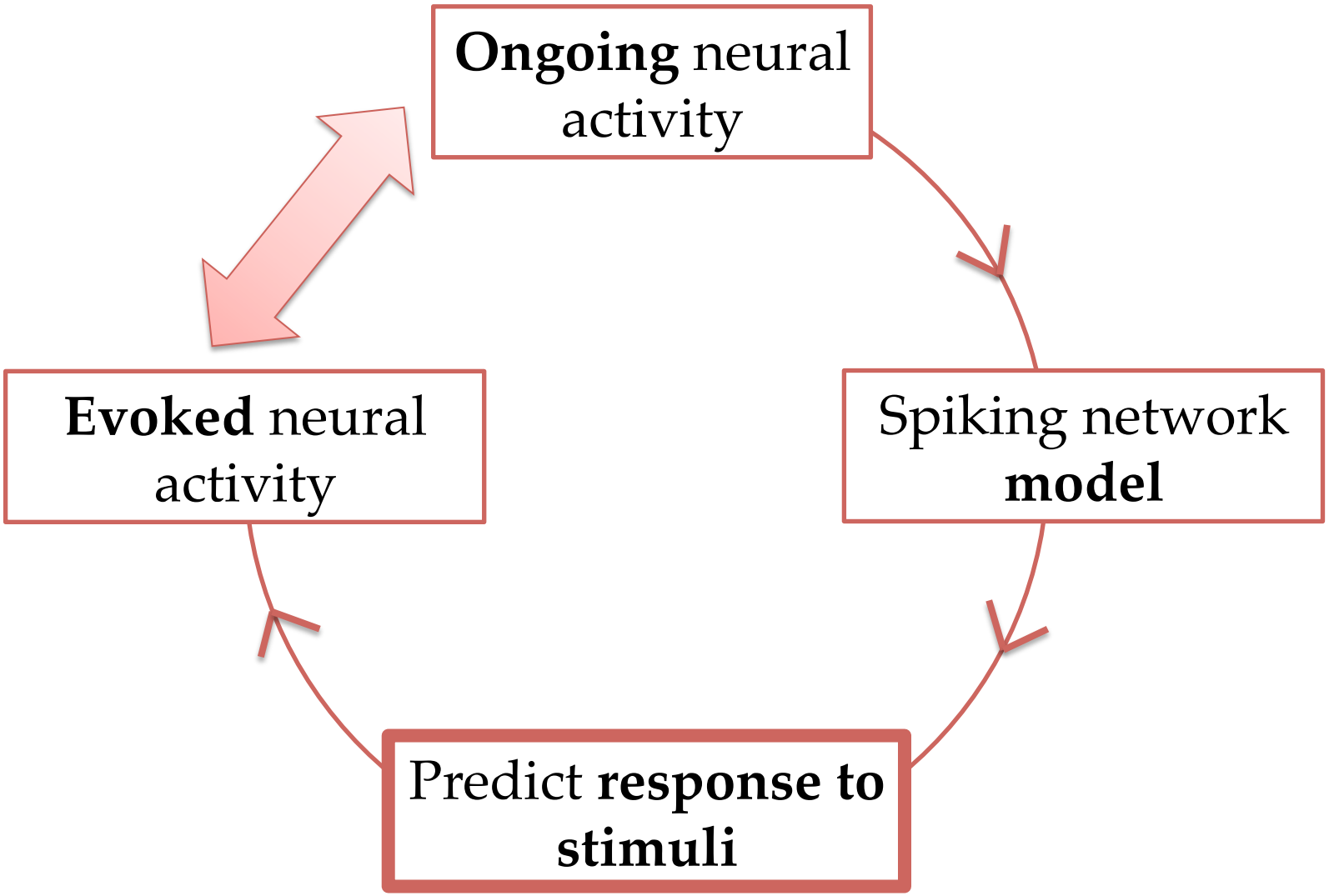
Covariance

$$d = \frac{(\mathrm{Tr}[C])^2}{\mathrm{Tr}[C^2]} = \left(\sum_{i=1}^{N} \hat{\lambda}_i^2 \right)^{-1}$$

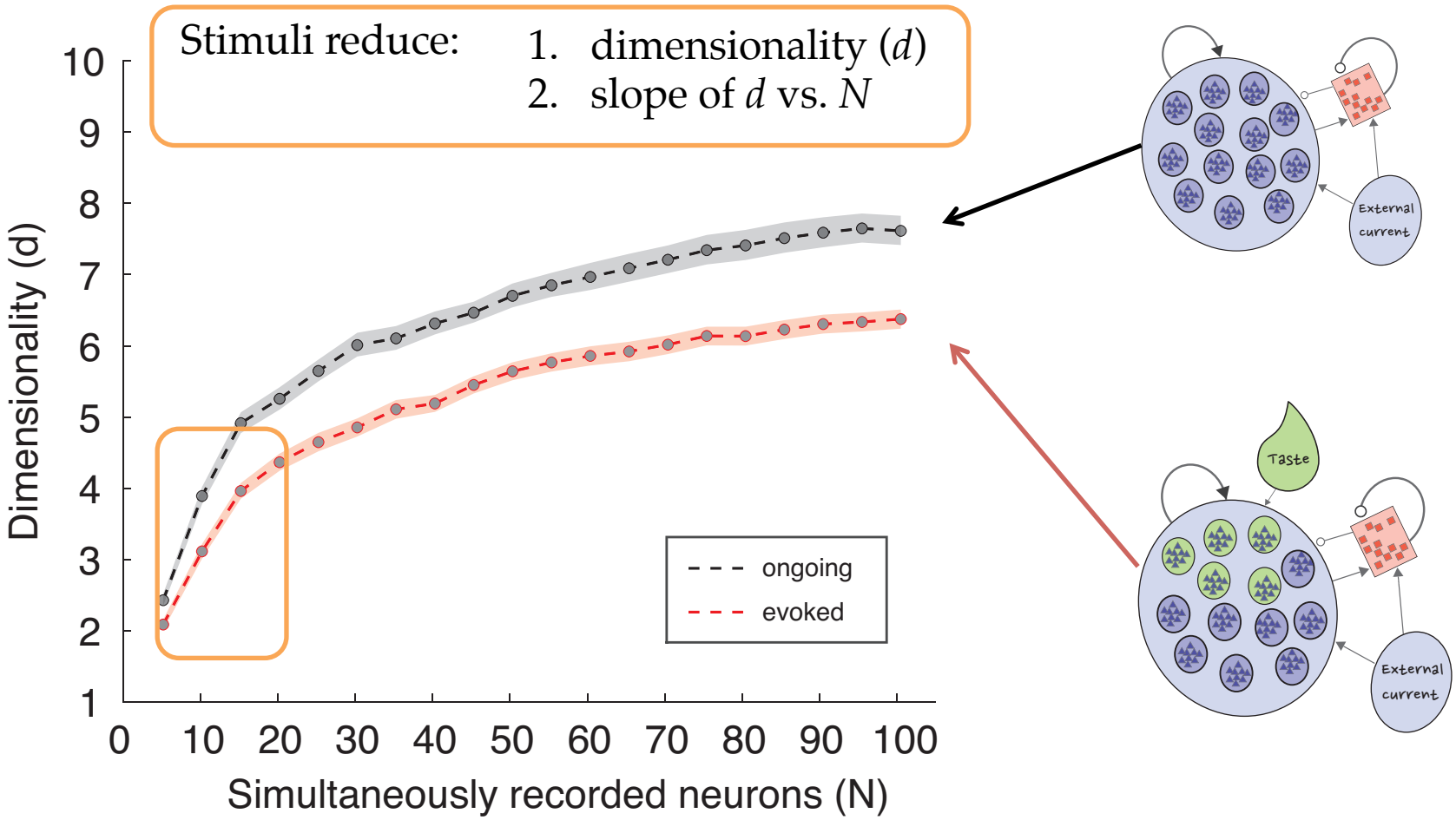
Principal Eigenvalues (normalized)

Abbott et al., 2011
Mazzucato et al., 2016

A unifying approach

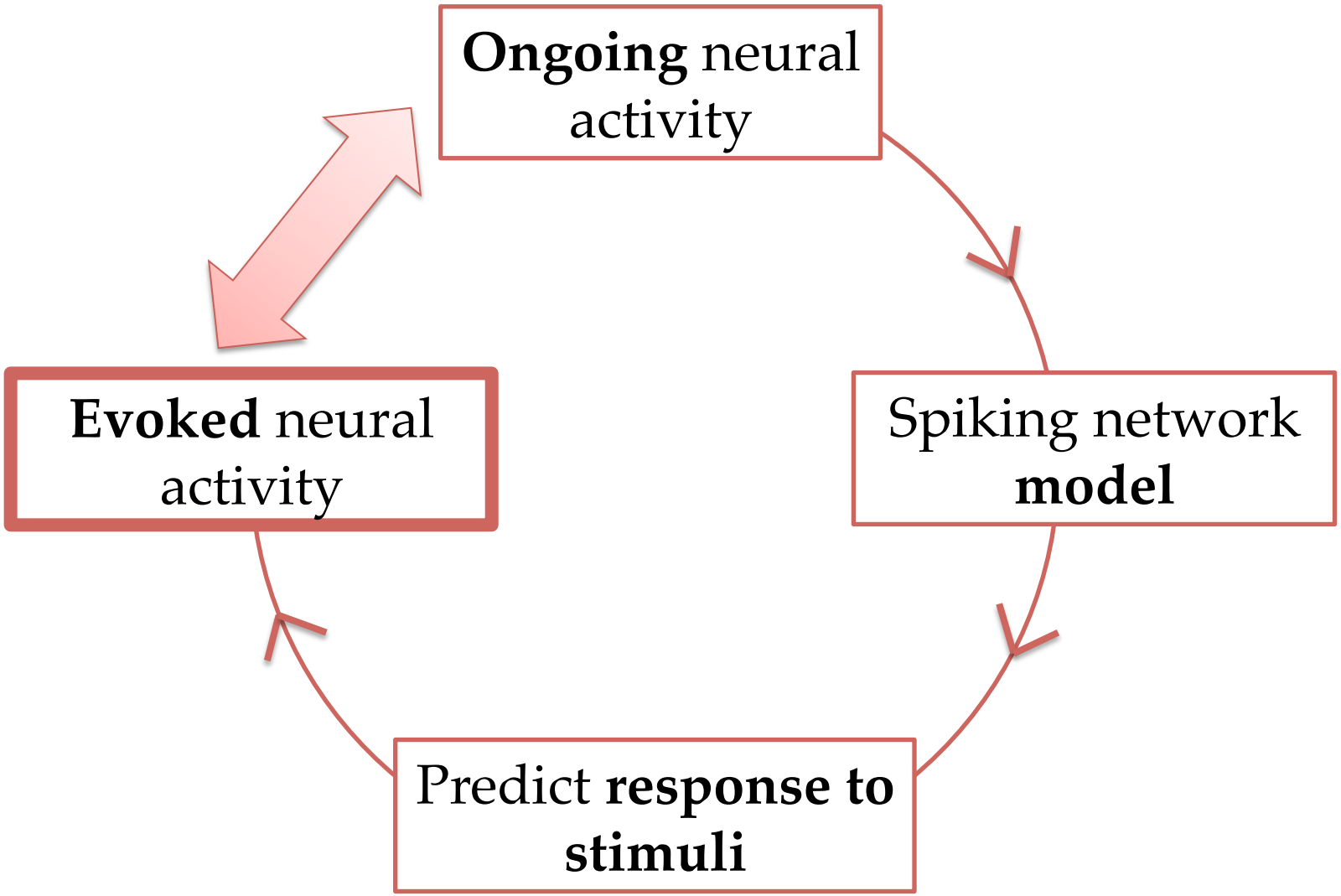


Model predictions



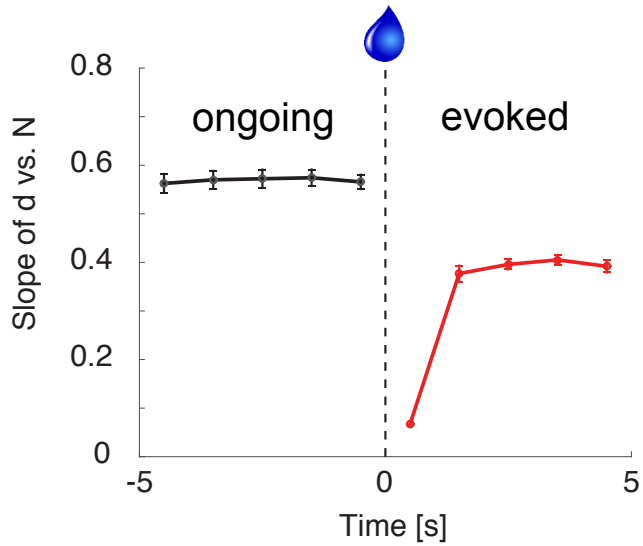
Mazzucato et al., 2016

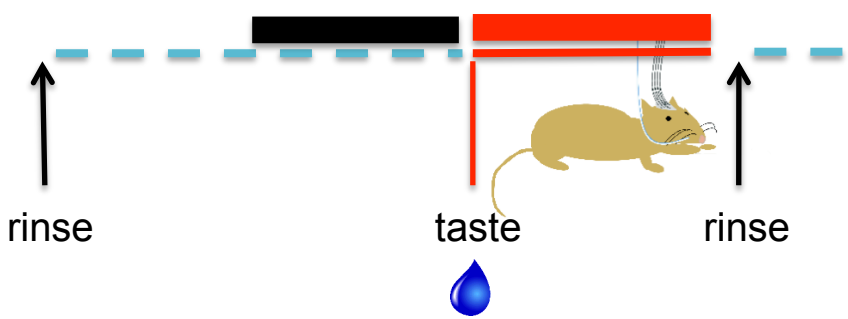
A unifying approach



Taste-evoked activity

Stimuli reduce:
1. dimensionality (d)
2. slope of d vs. N

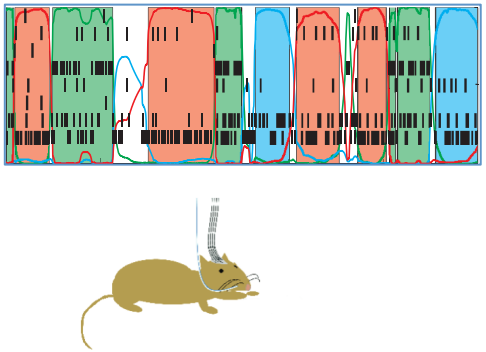


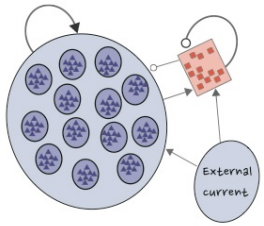


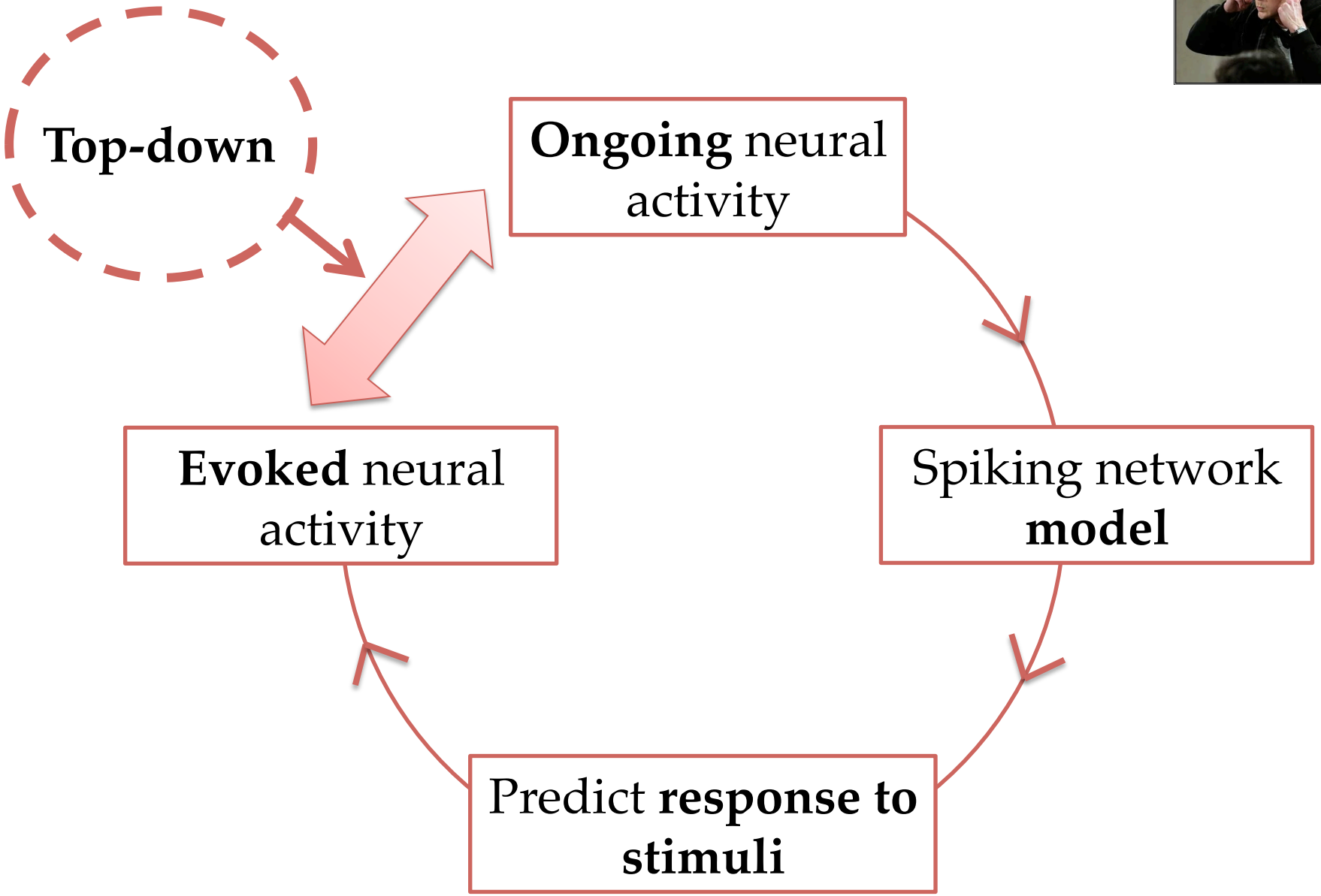
Mazzucato et al., 2016

A bottom-up approach to sensory processing

- Ongoing activity in taste cortex - we discovered:
  - State sequences
  - Multistability (42% neurons have ≥ 3 firing rates)
- Mechanistic model predicts response to stimuli.
- Stimuli reduce multistability & dimensionality.






Top-down
Ongoing neural activity
Spiking network model
Predict response to stimuli
Evoked neural activity

Expectations bias sensory processing

Expectations bias sensory processing

Classical conditioning: Expectation of a stimulus speeds up sensory processing

Conditioned stimulus

Unconditioned stimulus

Samuelsen et al., 2012

Acknowledgements

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Giancarlo La Camera

and members of Fontanini's and La Camera's labs

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NIDCD

K25-DC013557

THE SWARTZ FOUNDATION

Swartz 66438

Those who sacrificed their lives

Thank you!