Hold that thought: neural circuits supporting persistent percepts

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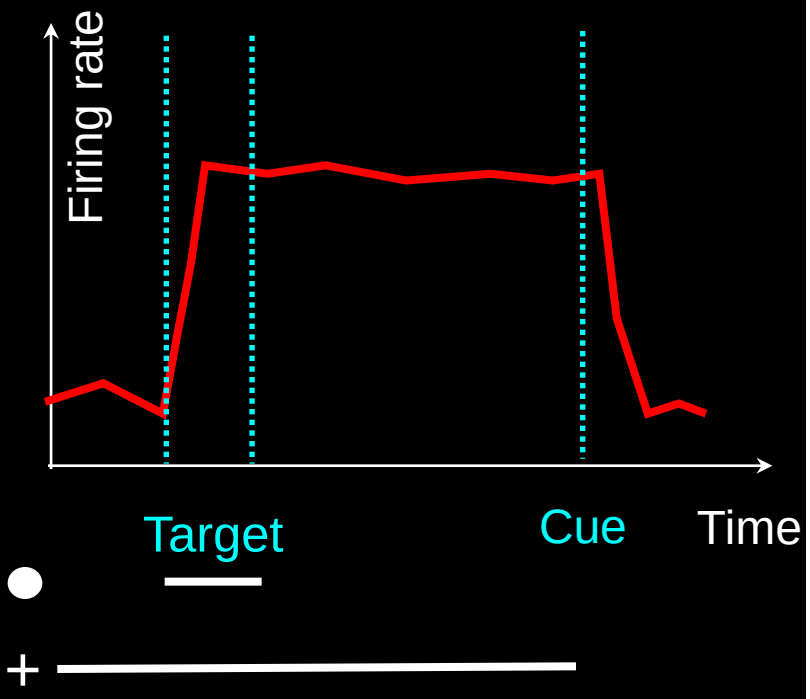
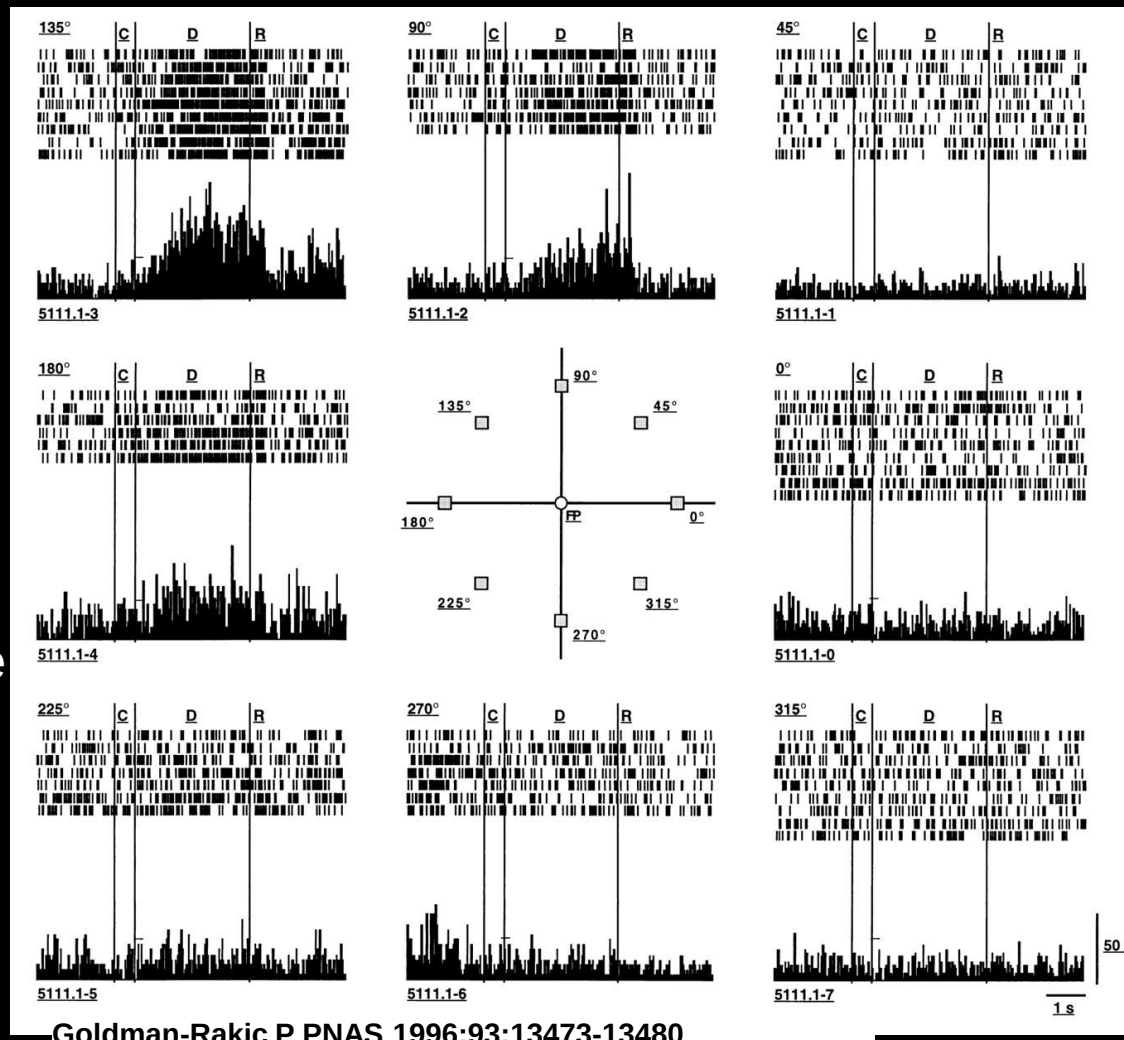
Working memory task

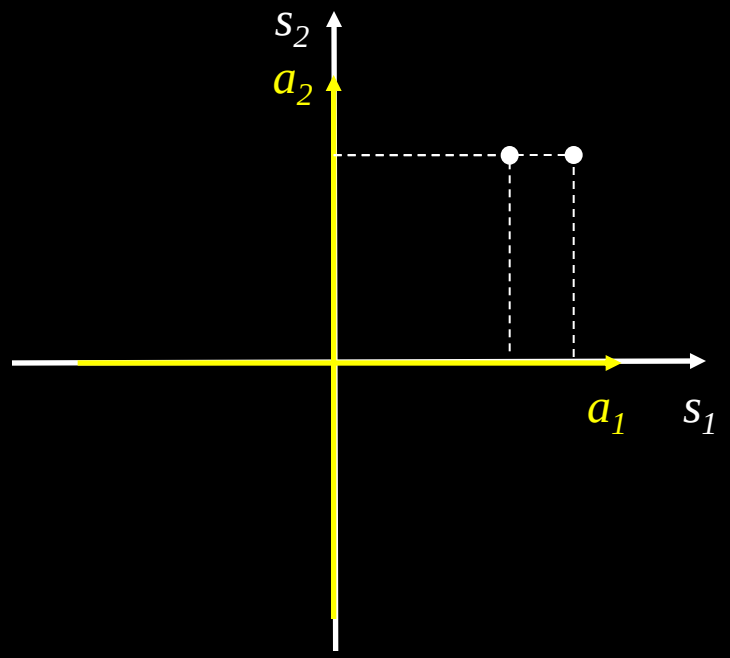
Conventional explanation: stimulus memory, or percept, is maintained by persistent activity

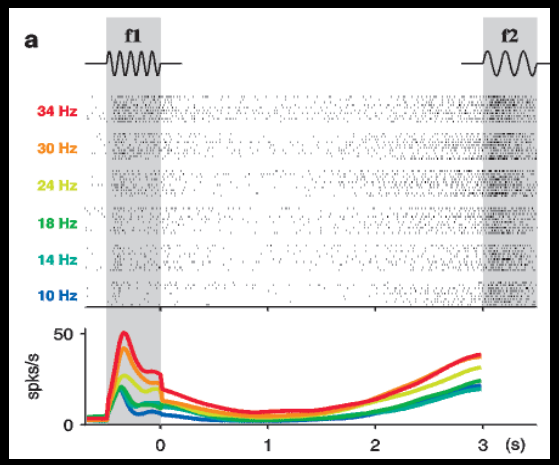




Goldman-Rakic P PNAS 1996;93:13473-13480

Representation of a sensory percept with neuronal activity





Brody, Hernandez, Zainos, Romo (2003)

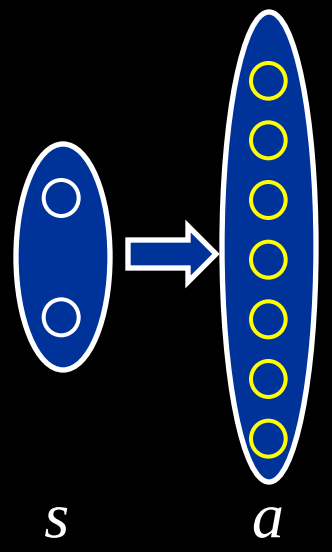
Orthogonal representation
Sensory dimensions: 2
Number of neurons, or activity dimensions: 2

How can time-varying neuronal activity support persistent percepts?

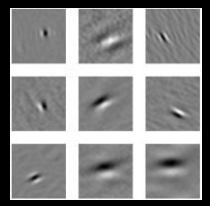
Redundant neural representations

Primary visual cortex

thalamic << # cortical
inputs neurons

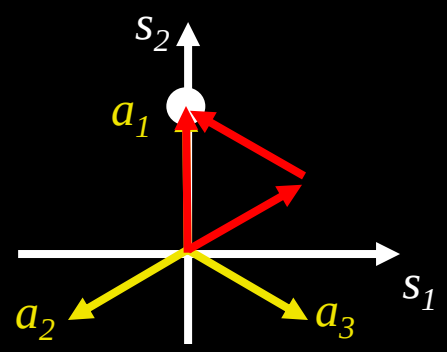


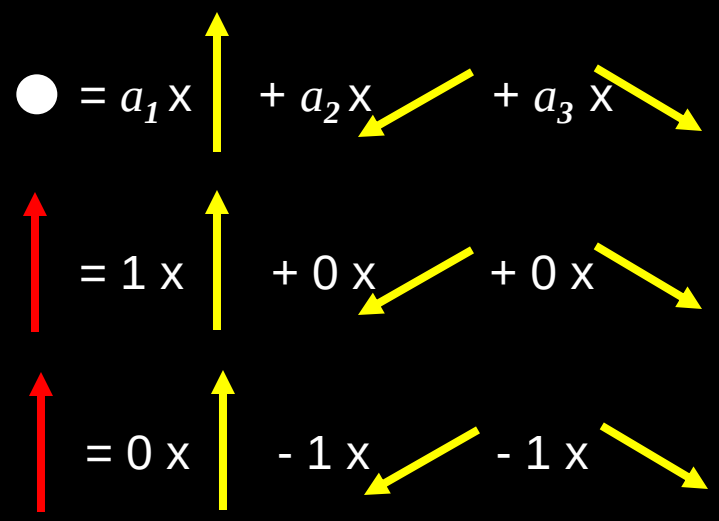
Non-orthogonal receptive fields in monkey V1 *(Ringach)*:



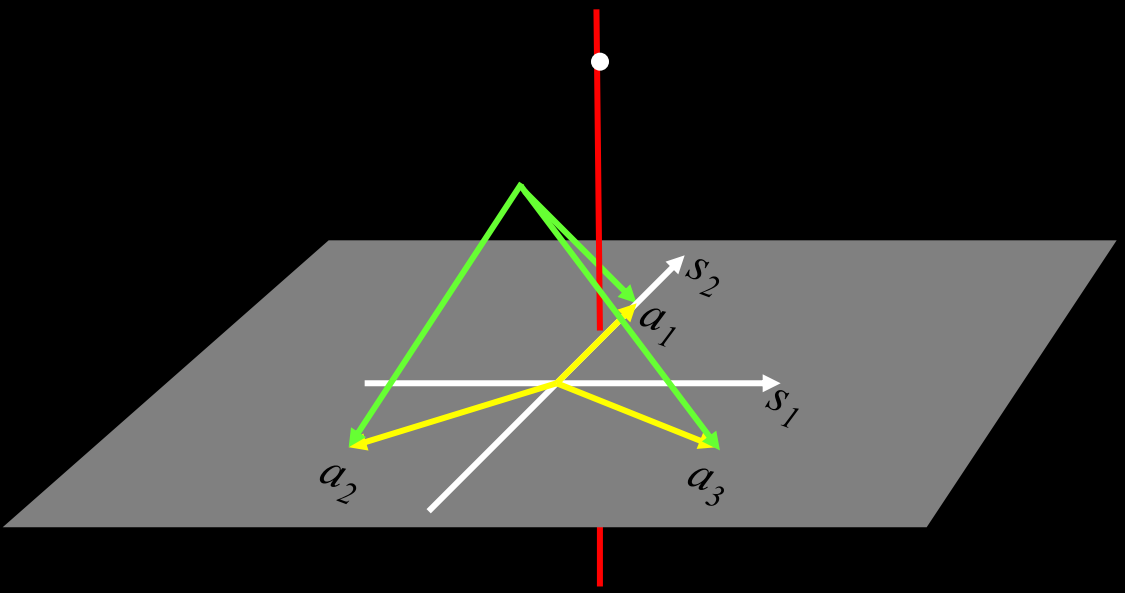
The Mercedes-Benz frame

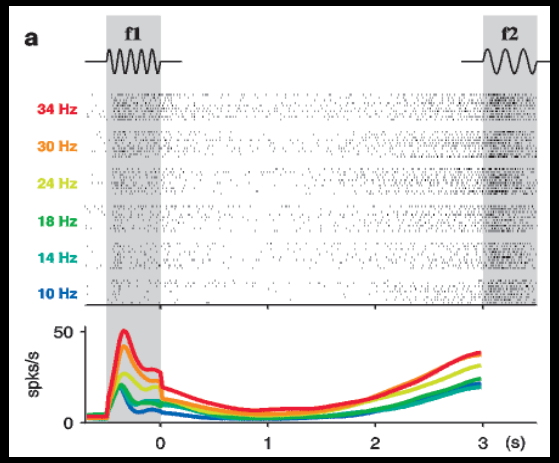
s - sensory percept: 2 dimensions
a – neural activity: 3 dimensions





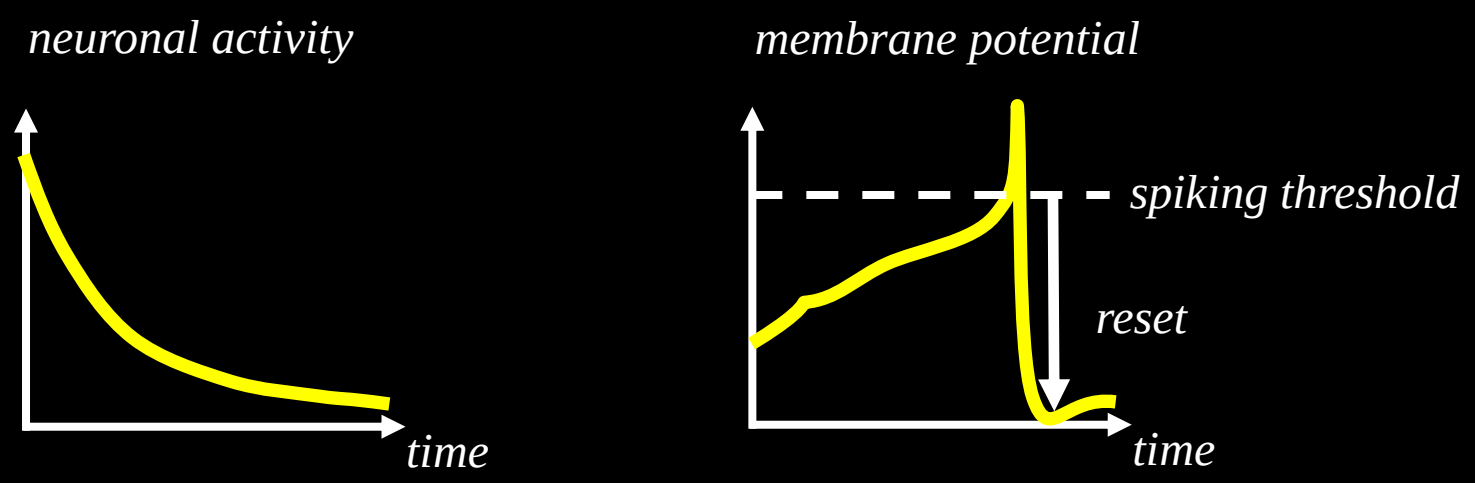
In a redundant representation, multiple neuronal activity patterns correspond to the same percept



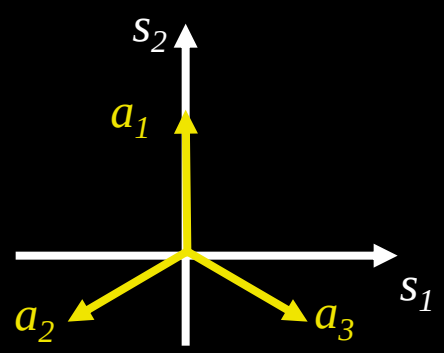


Brody, Hernandez, Zainos, Romo (2003)

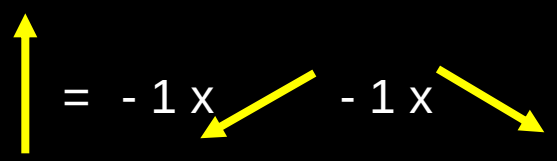
How can percept-preserving dynamics be generated in neurons?

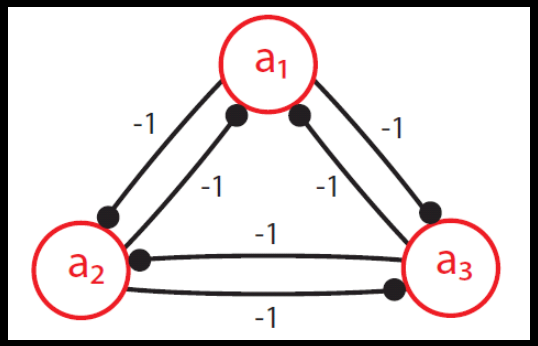


A circuit supporting persistent percepts in the Mercedes-Benz frame

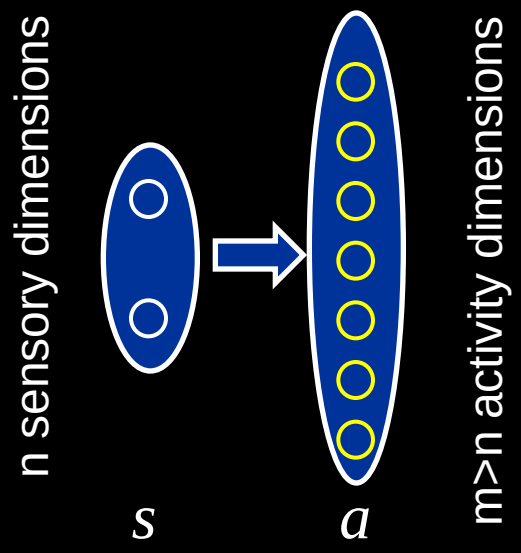


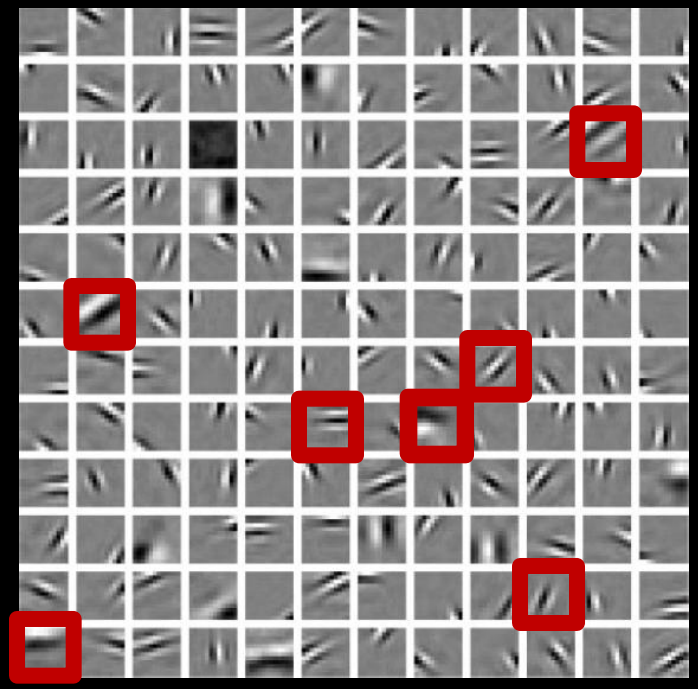
Vector re-expression



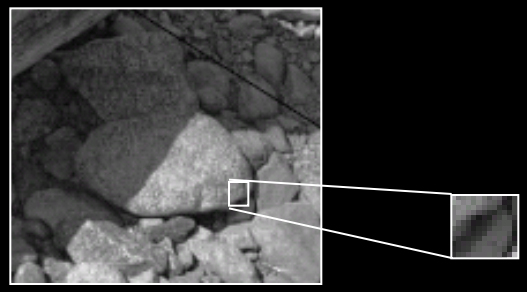


Representation of a visual percept as a linear combination of V1 feature vectors, or receptive fields





Olshausen & Field (1996)

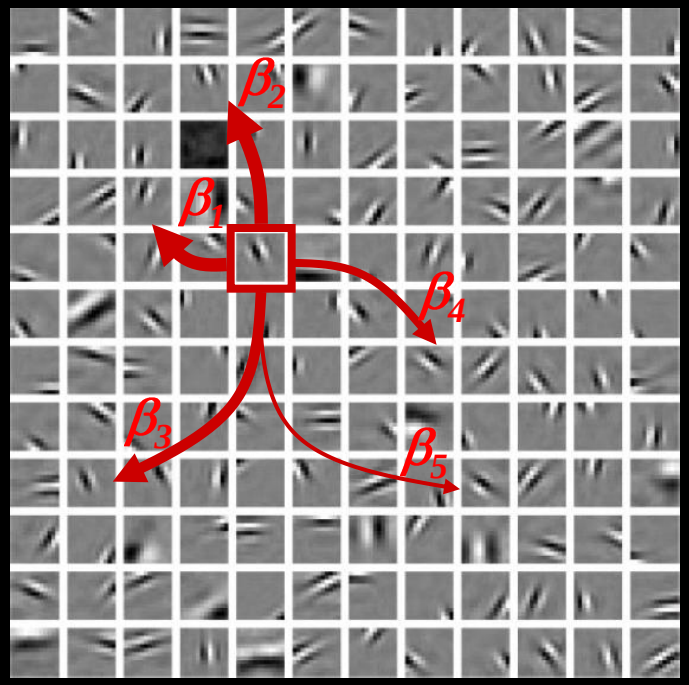


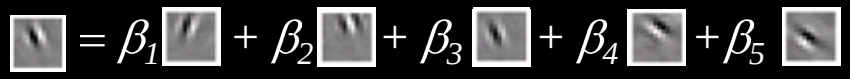
$= a_1$  $+ a_2$  $+ a_3$  $+ a_4$ 

 $= a'_1$  $+ a'_2$  $+ a'_3$  $+ a'_4$ 

Neural circuits supporting persistent percepts:

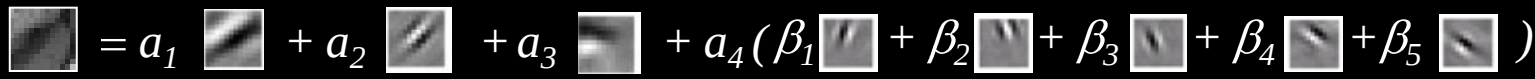
REceptive FIeld REcombination (REFIRE) networks



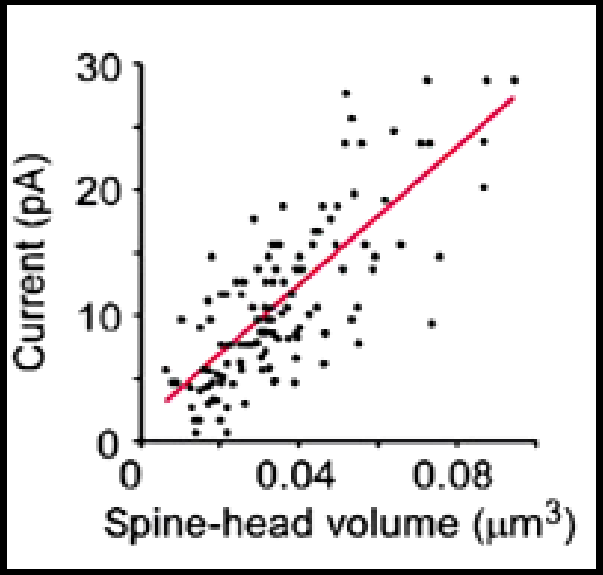


before reset of a_4:

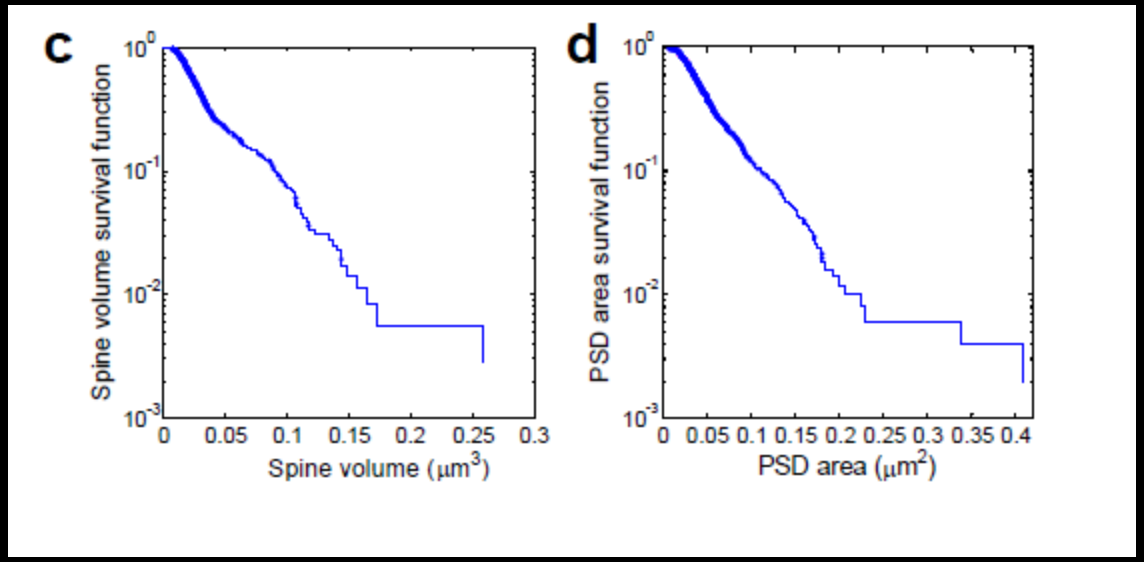
after reset of a_4:



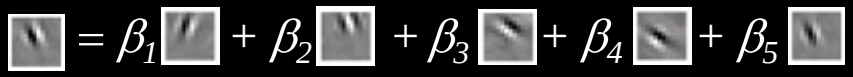
Choosing a particular REFIRE network: economy of synaptic volume/weight



Matsuzaki, Ellis-Davies, Nemoto, Miyashita, Iino & Kasai (2001)



Mischenko, Hu, Spacek, Mendenhall, Harris, Chklovskii (2010)

$\vec{\beta} = \text{argmin}\ \{ \Sigma_i \mid \beta_i \mid \}$ such that 

Sparsest REFIRE network computed for V1 feature vectors

Choose a sparse decomposition of feature vectors that minimizes total synaptic weight, or volume cost:

$$\mathbf{D_j} = \mathbf{d_1}, \mathbf{d_2}, \ldots \mathbf{d_{j-1}}, \mathbf{d_{j+1}} \ldots \mathbf{d_m}$$

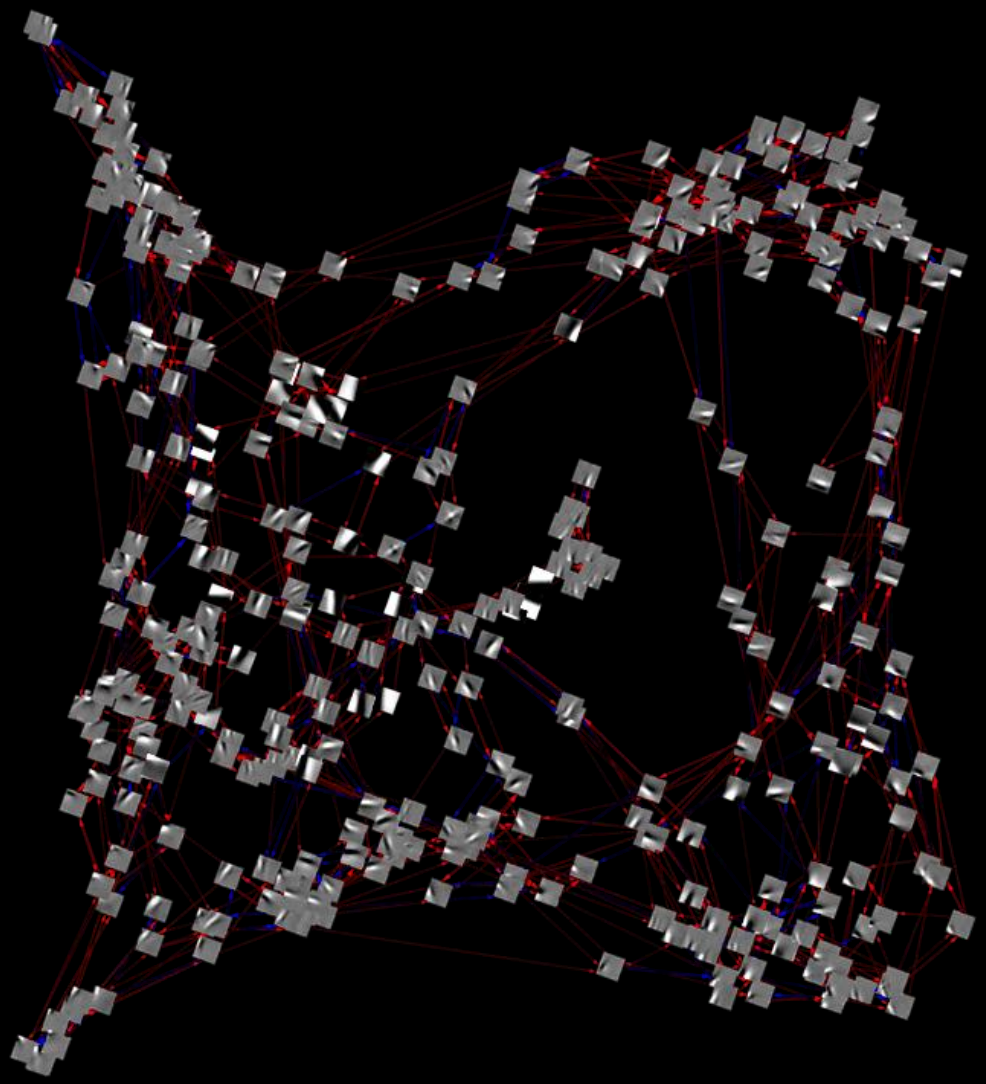
$$\beta_j^* = \min_{\beta_\mathbf{j} \in \mathcal{R}^{m-1}} ||\mathbf{d_j} - \mathbf{D_j}\beta_\mathbf{j}||_2^2 + \lambda_1 ||\beta_\mathbf{j}||_1$$

$$\mathbf{L} = [\tilde{\beta}_\mathbf{1}, \tilde{\beta}_\mathbf{2}, \ldots \tilde{\beta}_\mathbf{m}]$$

Weights computed using SPAMS package *(Mairal et al.)*

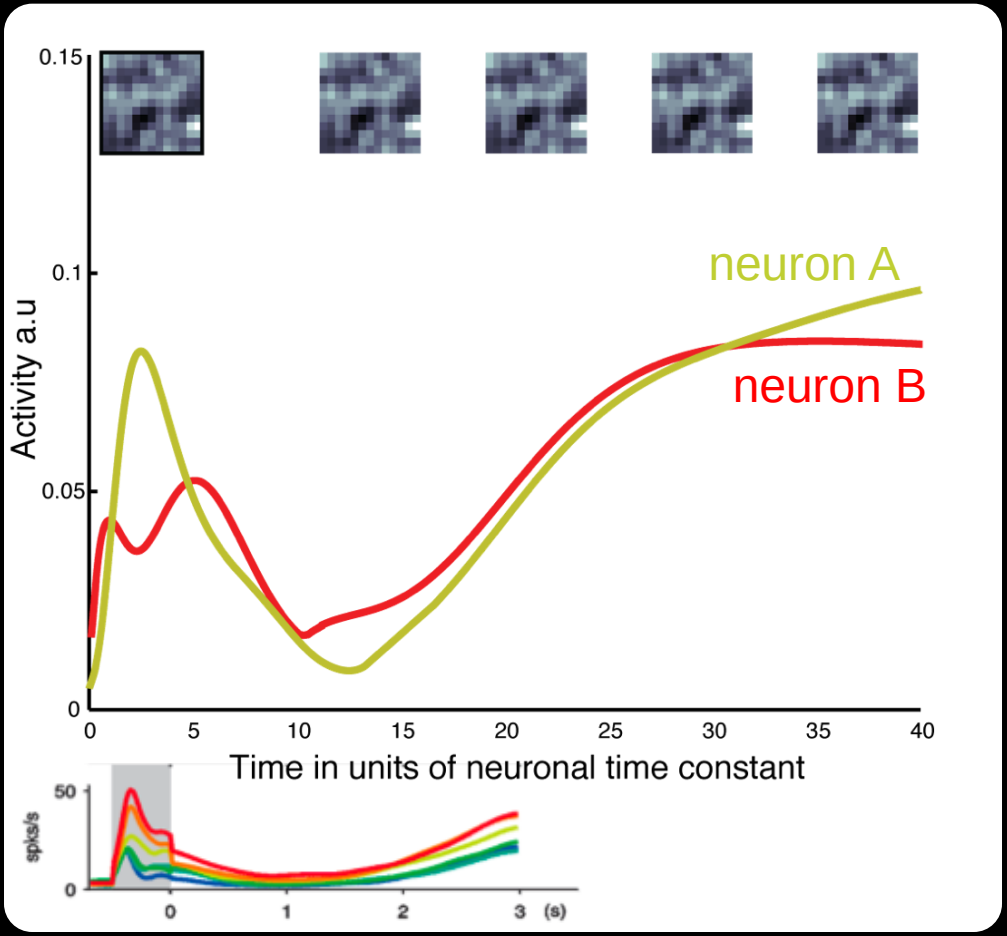
excitatory

inhibitory

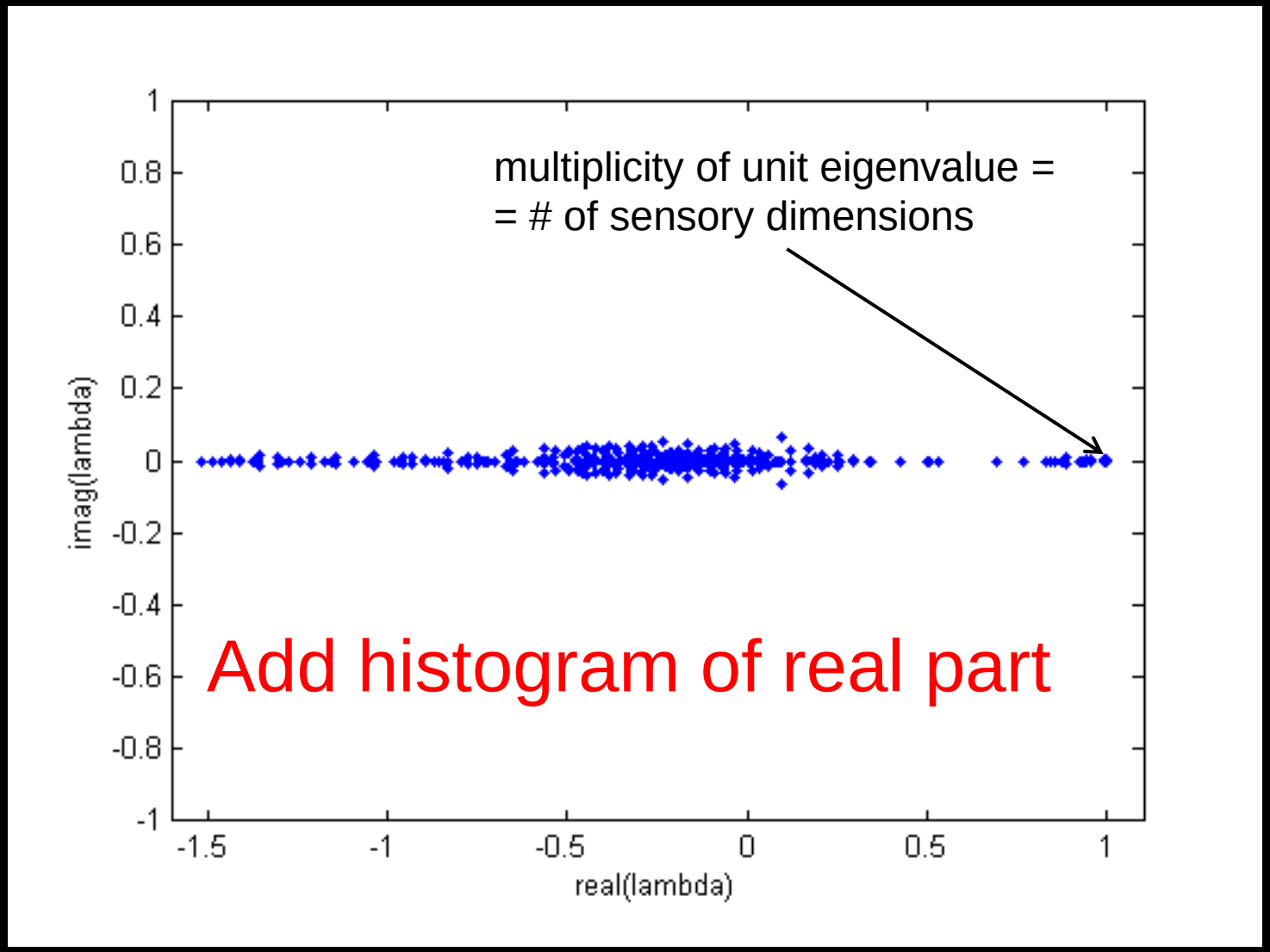


Only 10% of strongest connections are shown

Computer simulations: despite varying activity, percepts persist



Eigenspectrum of the sparsest REFIRE network



β = argmin { Σ_i | β_i | } shrinks Gershgorin circles restricting eigenvalue moduli to 1

Persistent percepts with non-linear dynamics

$$\begin{cases} s = D\,a \\ \dot{a} = (L - I)\,f \\ f = spike(a, 1) \end{cases}$$

s - sensory inputs (n)
D - over-complete dictionary
a – sub-threshold voltatge(m>n)
L – lateral connectivity matrix
f - supra-threshold voltage

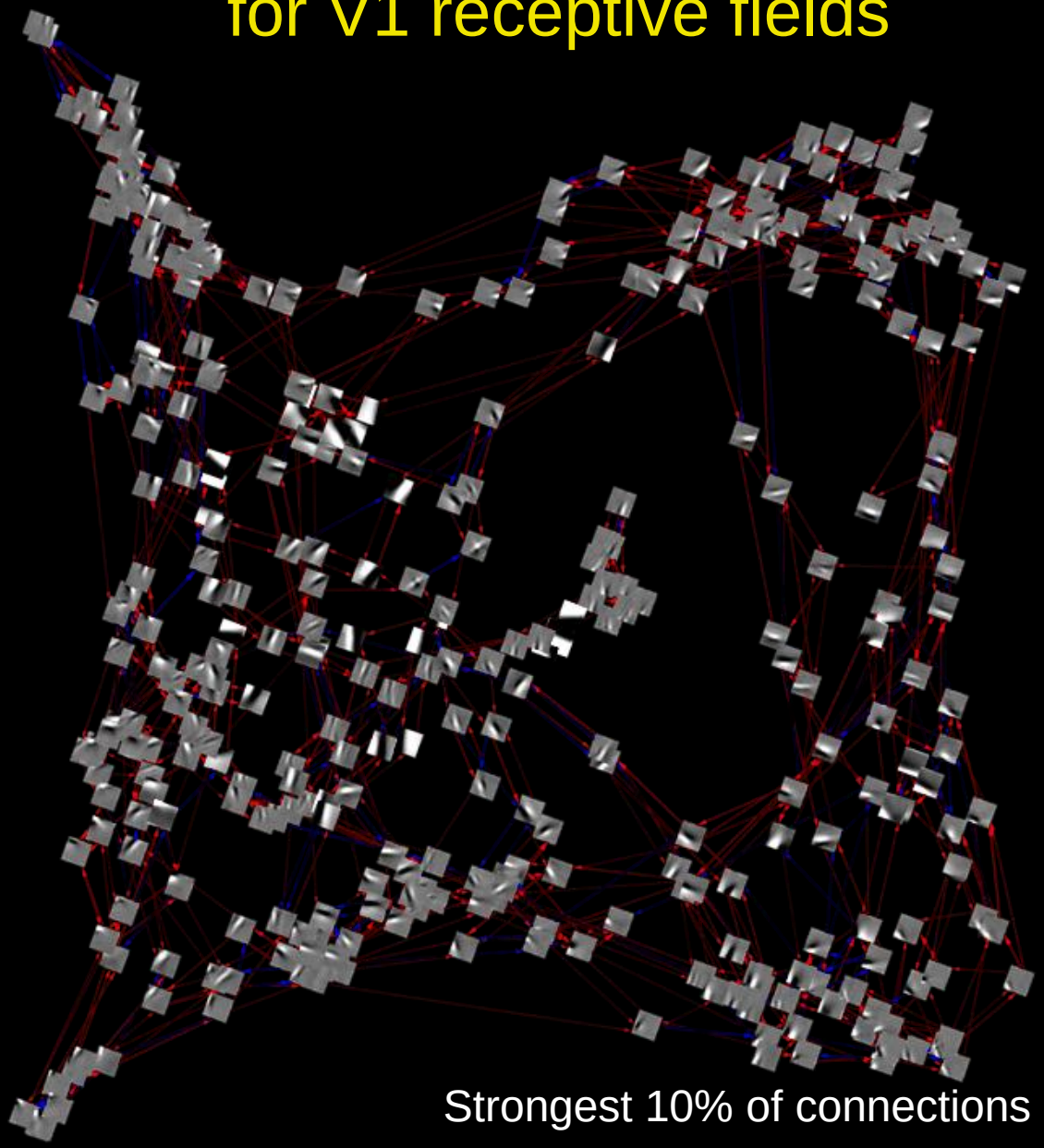
$$spike(a(\tau_0), 1) = \begin{cases} 0, & a(\tau_0) < 1 \\ \delta(\tau - \tau_0), & a(\tau_0) \geq 1 \end{cases}$$

$$\dot{s} = D\,\dot{a} = D(L - I)\,f = 0$$

Dynamical properties of the sparsest REFIRE circuit may account for several poorly understood properties of cortical networks

- Wide distribution of firing rates (*Koulakov, Hromadka & Zador, 2009*)
- Spike counts have high coefficient of variation (*Softky & Koch, 1993*)
- “Weak thalamic input” dominates neuronal responses despite much more numerous recurrent cortical connections (*Douglas, Koch, Machowald, Martin & Suarez, 1995*)

Sparsest REFIRE circuit computed for V1 receptive fields



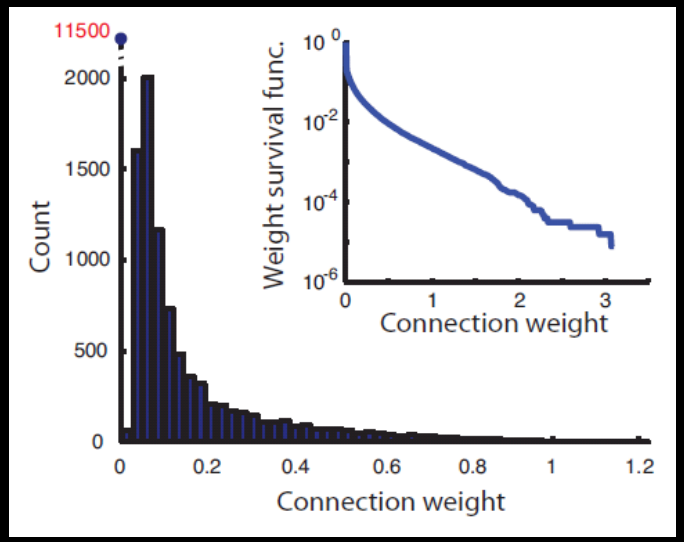
excitatory

inhibitory

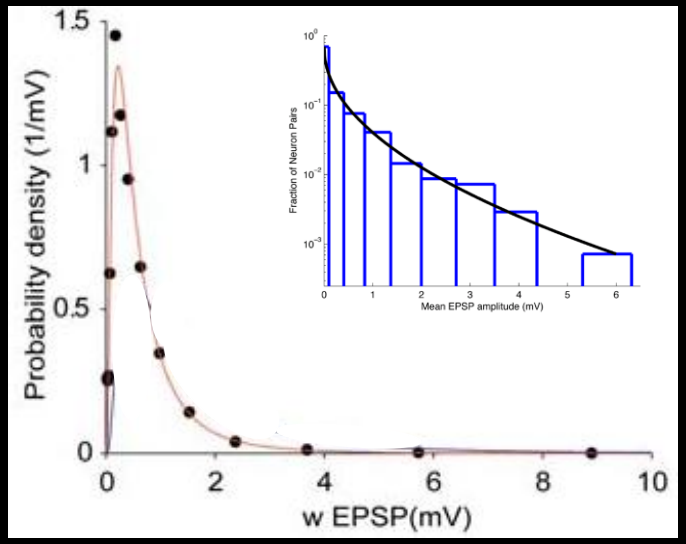
Strongest 10% of connections

Distribution of connection weights

Model network



Experiment: rat visual cortex



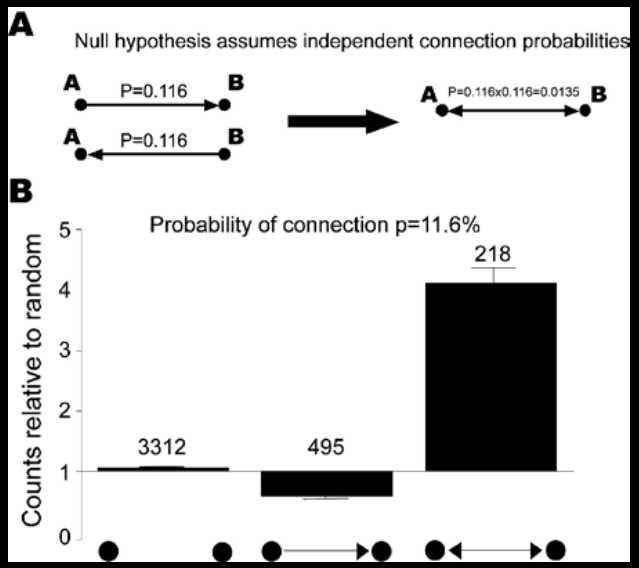
Song, Sjostrom, Reigl, Nelson, Chklovskii (2005)

Frequency of reciprocal connections matches experiments

Model network

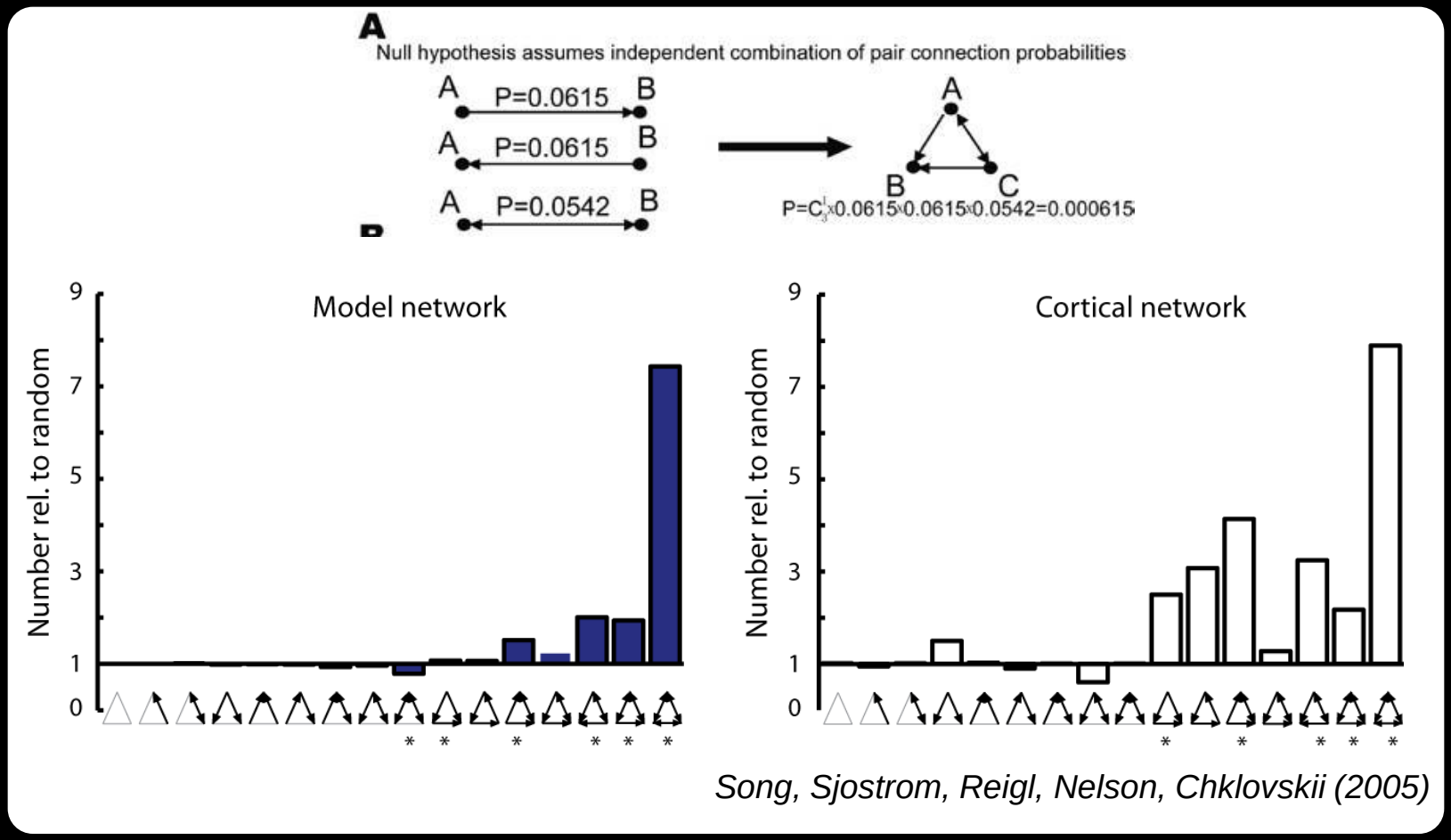
$P_{=>} = 0.09$ $P_{\Leftrightarrow} = 0.03$

Experiment: rat visual cortex



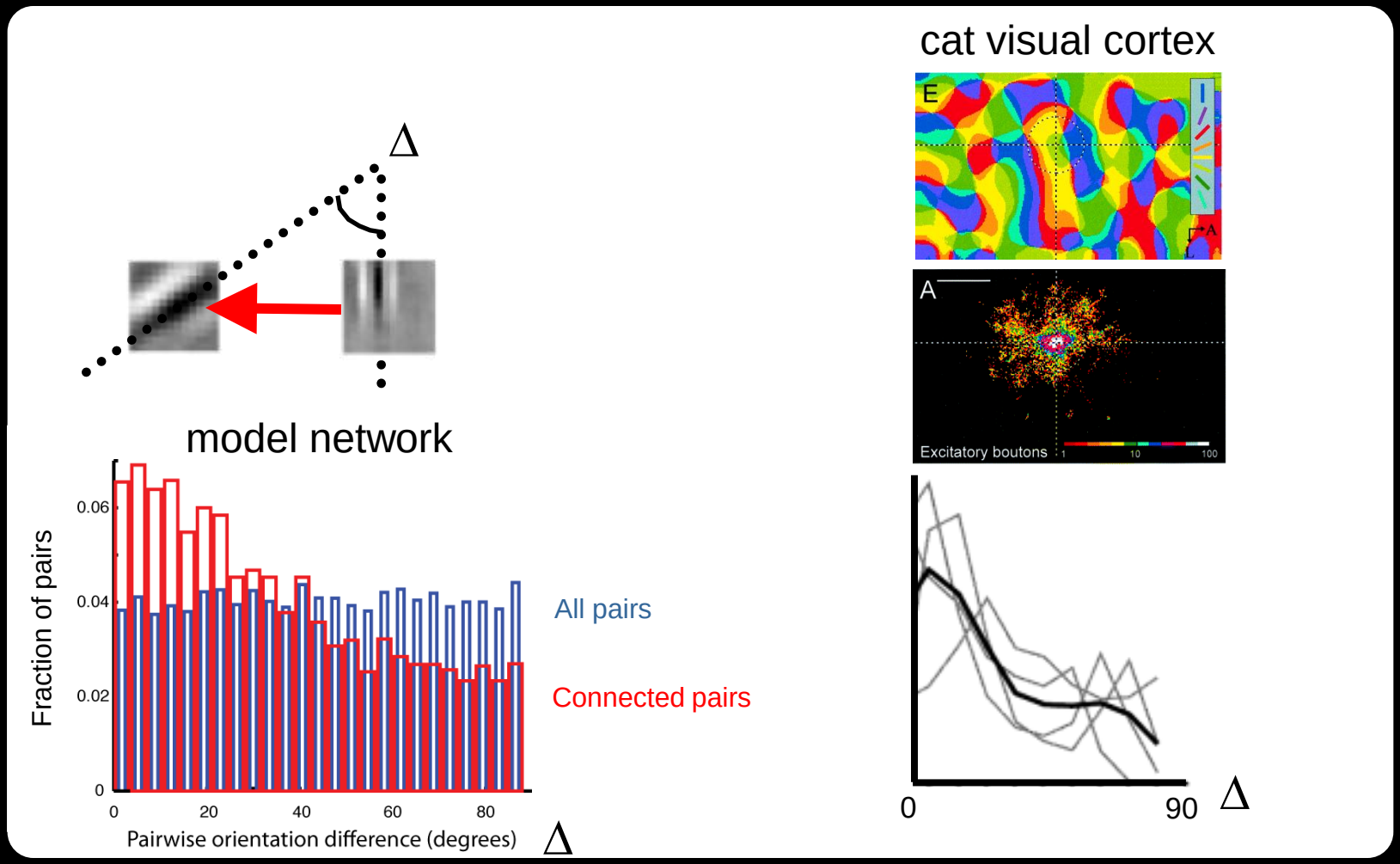
Song, Sjostrom, Reigl, Nelson, Chklovskii (2005)

Network motifs match experiments



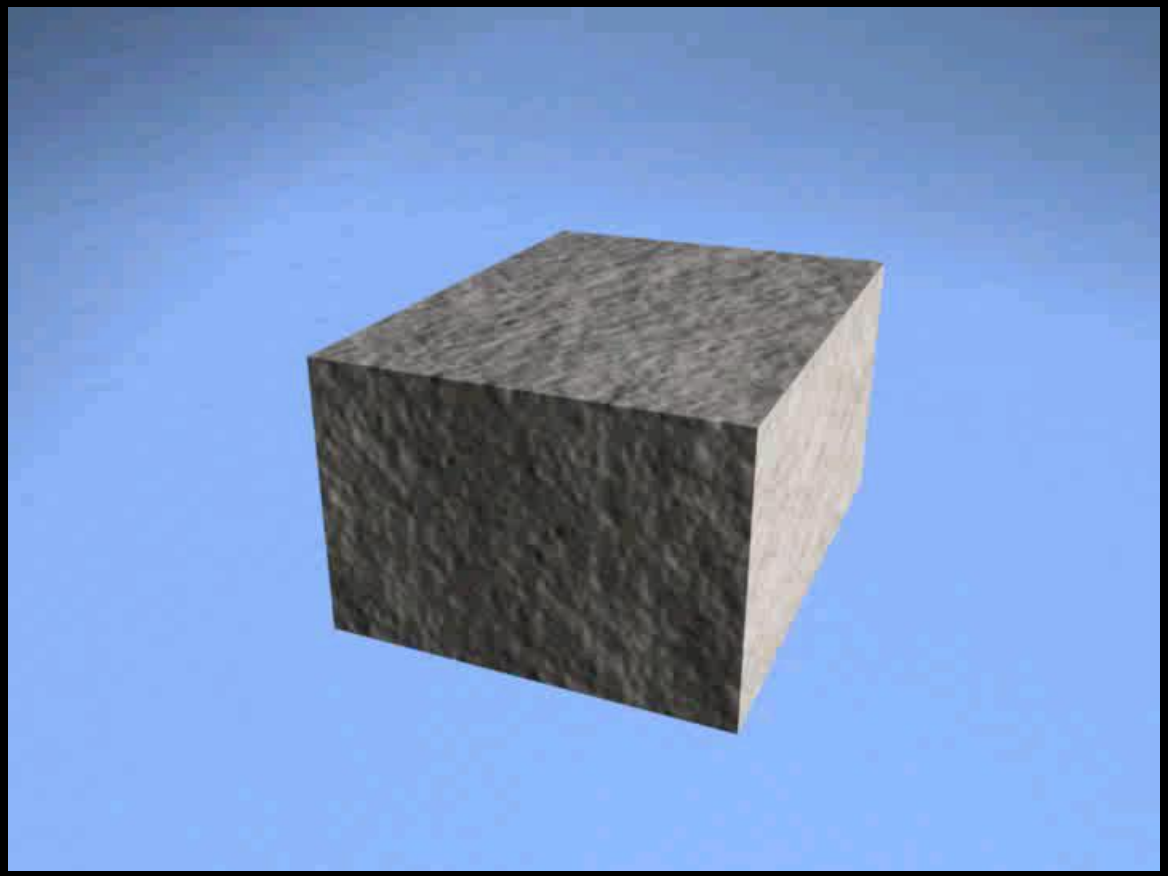
Song, Sjostrom, Reigl, Nelson, Chklovskii (2005)

Orientation preference of lateral connections



Youssef et al. (1999)

Reconstruction of neural circuits using electron microscopy (EM)

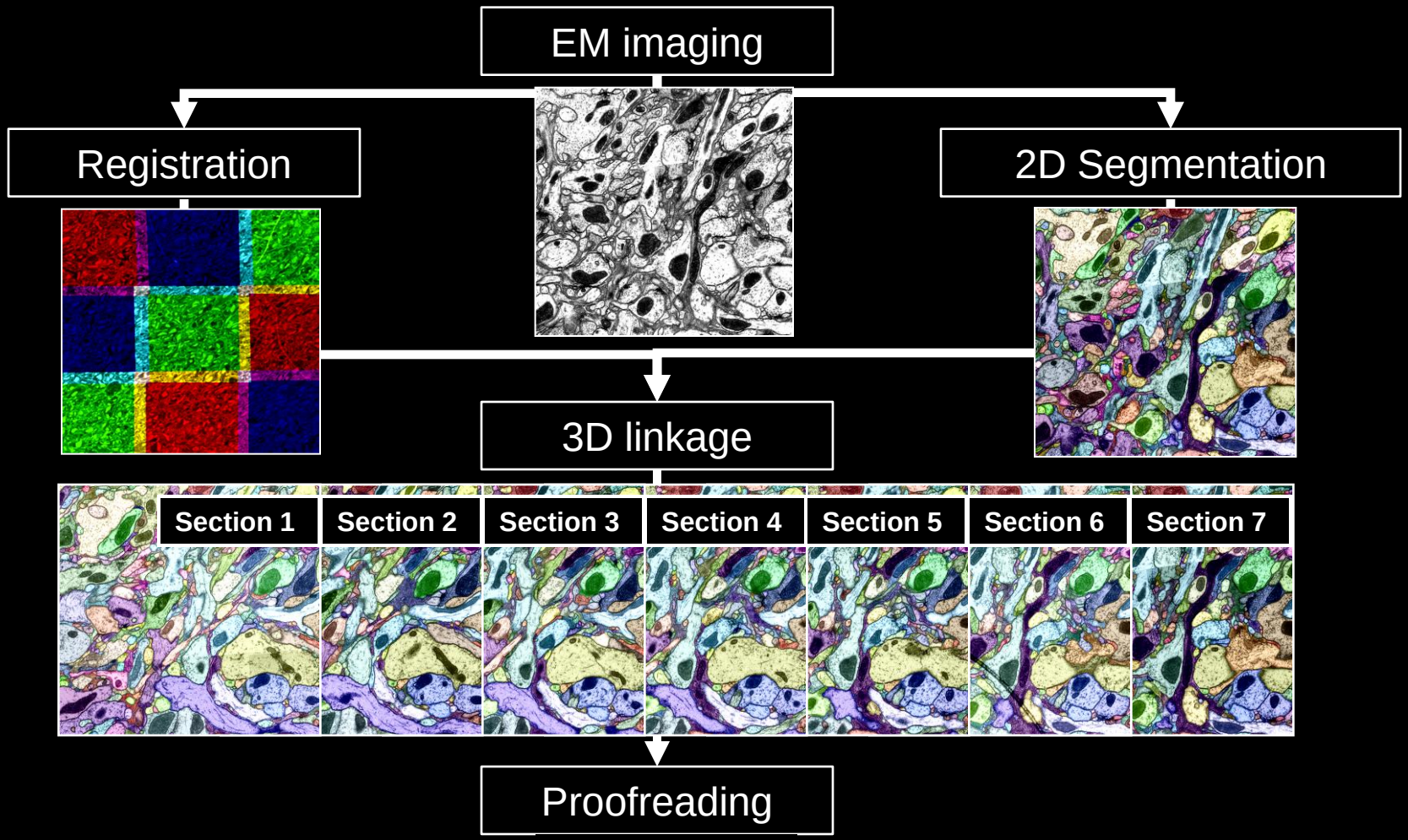


Volume 10x10x10 micron^3

- Tissue preparation and sectioning ~ days
- Image acquisition ~ days
- Circuit reconstruction ~ year

Grand challenge for computer vision

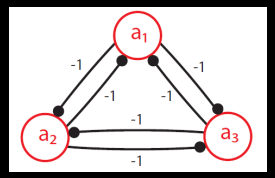
Janelia Farm reconstruction pipeline



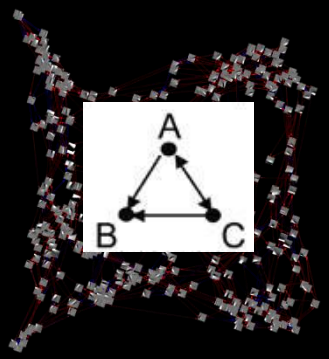
Fly vision circuits

Summary

In a redundant representation, some changes in activity do not change the percept. Such decoupling of representation and activity offers computational advantages



Contribution of a neuron to a representation lost to post-spiking reset, or leakiness, can be compensated by distributing activity to other neurons via appropriately weighted connections (REFIRE circuit)

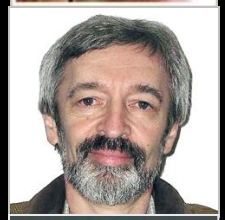
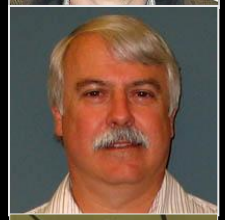


Sparsest REFIRE circuit shares many anatomical and physiological properties with the cortical network in V1 and other cortical areas

Test the REFIRE hypothesis by large scale circuit reconstructions

Acknowledgements



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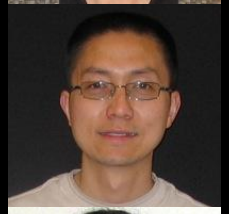
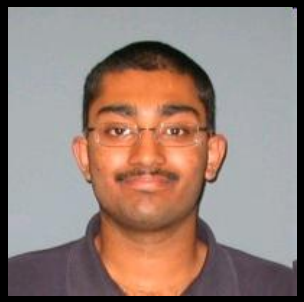




The Chklovskii group



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Postdoctoral and research scientist positions available