# Presence of high order cell assemblies in mouse visual cortices during natural movie stimulation

**ICMNS 2017**

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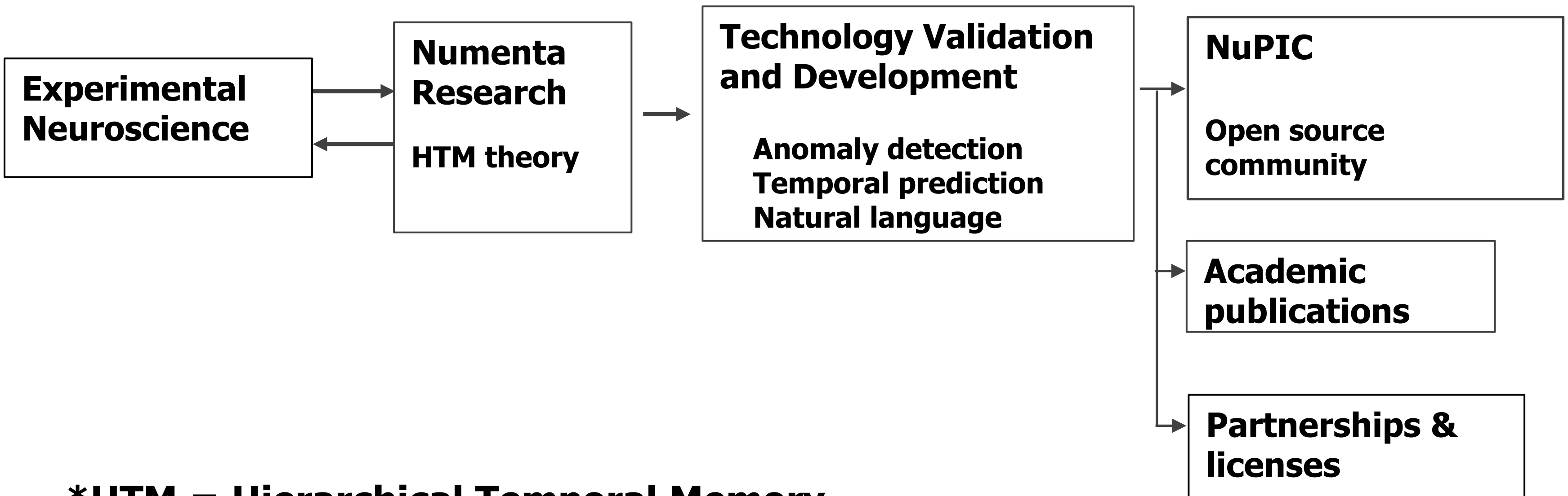
# Numenta’s Approach

**1) Discover operating principles of the neocortex**
**2) Create technology based on those principles**




***HTM = Hierarchical Temporal Memory**

# Outline

- Cell assemblies and the HTM Model Neuron
- Network of neurons learn sequences
- Testable predictions of HTM
- Presence of cell assemblies in the mouse visual cortex

## Cell assemblies

- Donald Hebb: neurons do not function in isolation but are organized in assemblies.

- Cell assembly: “a diffuse structure comprising cells in the cortex and diencephalon, capable of acting briefly as a closed system, delivering facilitation to other such systems”.
  - "The Organization of Behavior" (1949)

**How does cortex compute with cell assemblies?**

**How do neurons form and recognize cell assemblies?**

frontiers in Neural Circuits

HYPOTHESIS & THEORY ARTICLE

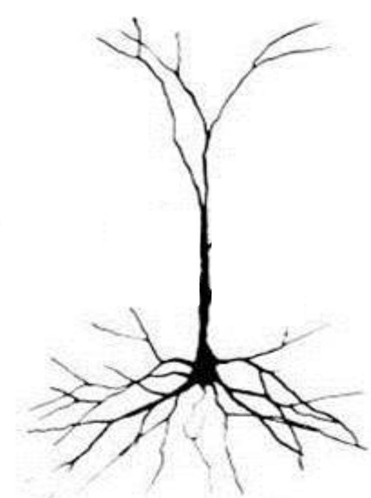
Front. Neural Circuits, 30 March 2016 | https://doi.org/10.3389/fncir.2016.00023



# Why Neurons Have Thousands of Synapses, a Theory of Sequence Memory in Neocortex

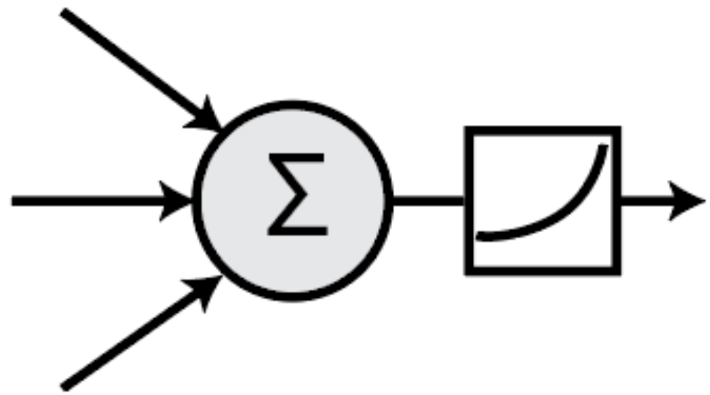
Jeff Hawkins* and Subutai Ahmad

Numenta, Inc., Redwood City, CA, USA



# Computation of a Neuron Lacking Dendrites

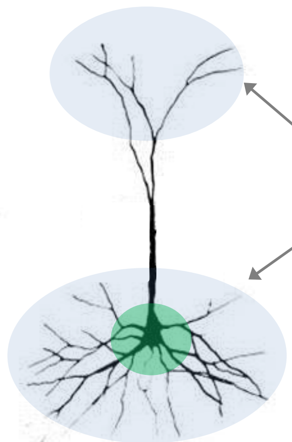
Point Neuron Model




"soma" "axon"

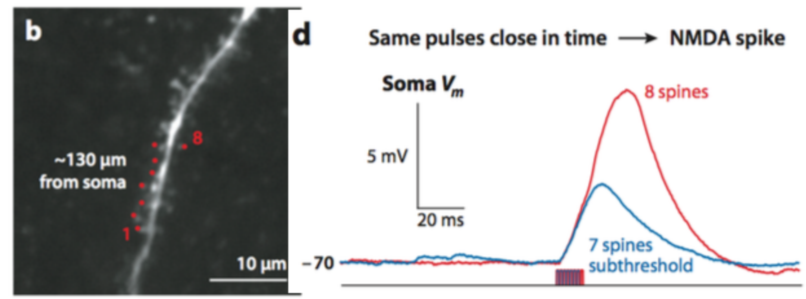
**Perceptron**, Rosenblatt 1962; Rumelhart et al. 1986; LeCun et al., 2015
**Integrate and fire neuron,** Lapicque, 1907
**LNP cascade mode**l, Chichilnisky 2001; Paninski 2004;

# Active Dendrites



Non-linear

8-20 coactive synapses lead to dendritic NMDA spikes



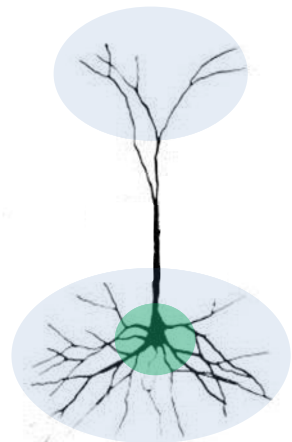

Major, Larkum and Schiller 2013

**Pyramidal neuron**

(Branco & Häusser, 2011; Schiller et al, 2000; Losonczy, 2006; Antic et al, 2010; Major et al, 2013; Spruston, 2008; Milojkovic et al, 2005, etc.)

**Cell assemblies are required to trigger dendritic spike.**

# What Computation do Active Dendrites Perform?



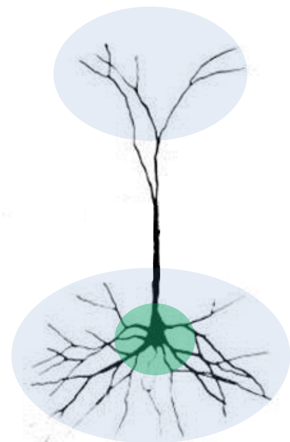
**Pyramidal neuron**

Active dendrites exist to boost/normalize the effects of distal synapses, leading in the end to a more linear, point-neuron-like cell.

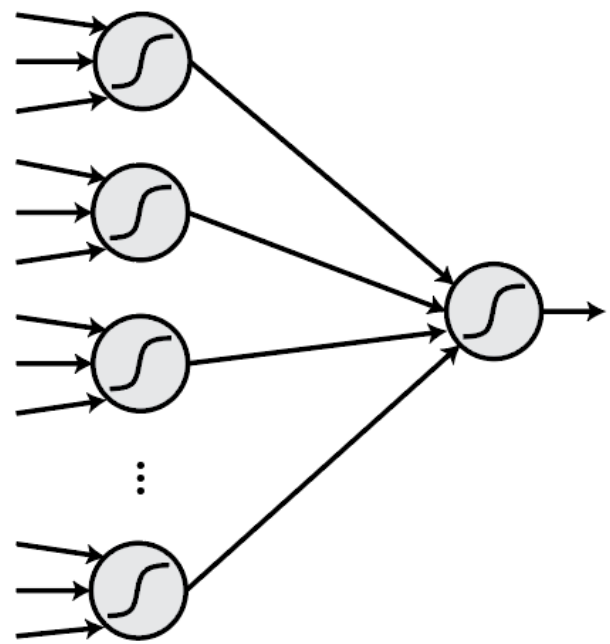
(Spencer and Kandel 1961; Shepherd et al. 1985; Cauller and Conors 1992; Bernander, Koch et al. 1994; De Schutter and Bower 1994; Cook and Johnston 1997; Magee 1998; Cash and Yuste 1999; Williams and Stuart 2000; London and Hausser 2005).

Neurons with active dendrites can exhibit integrative behaviors more complex than that of a point neuron.

# What Computation do Active Dendrites Perform?



**Pyramidal neuron**



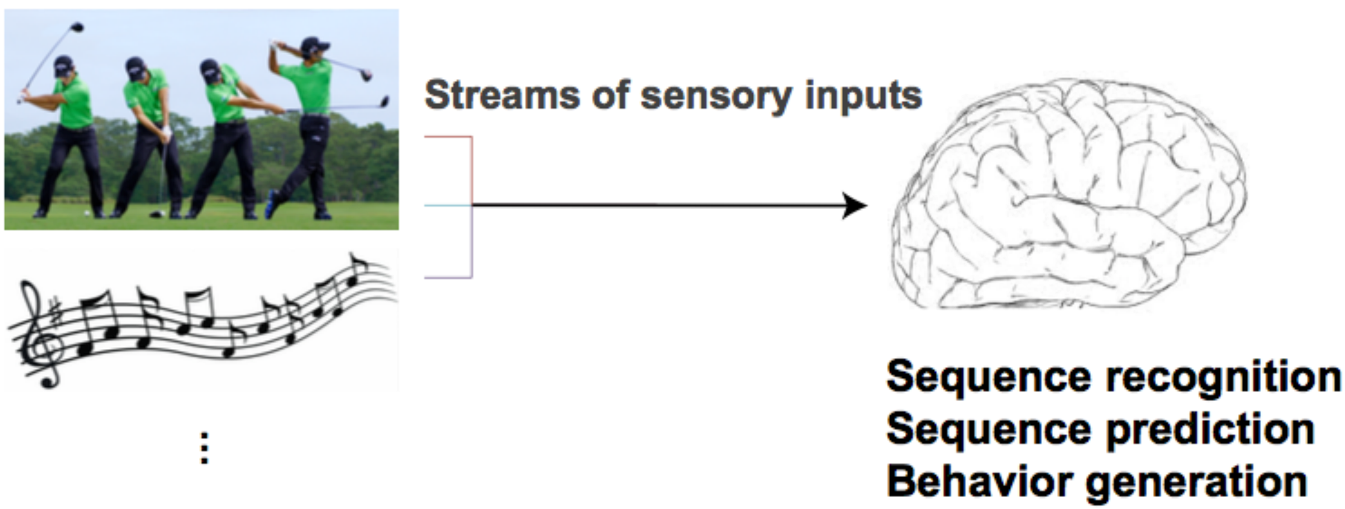

**Two layer neural network**

Mel 1992; Poirazi et al., 2003; Polsky et al., 2004
Koch & Poggio 1992; Shepherd and Brayton 1987

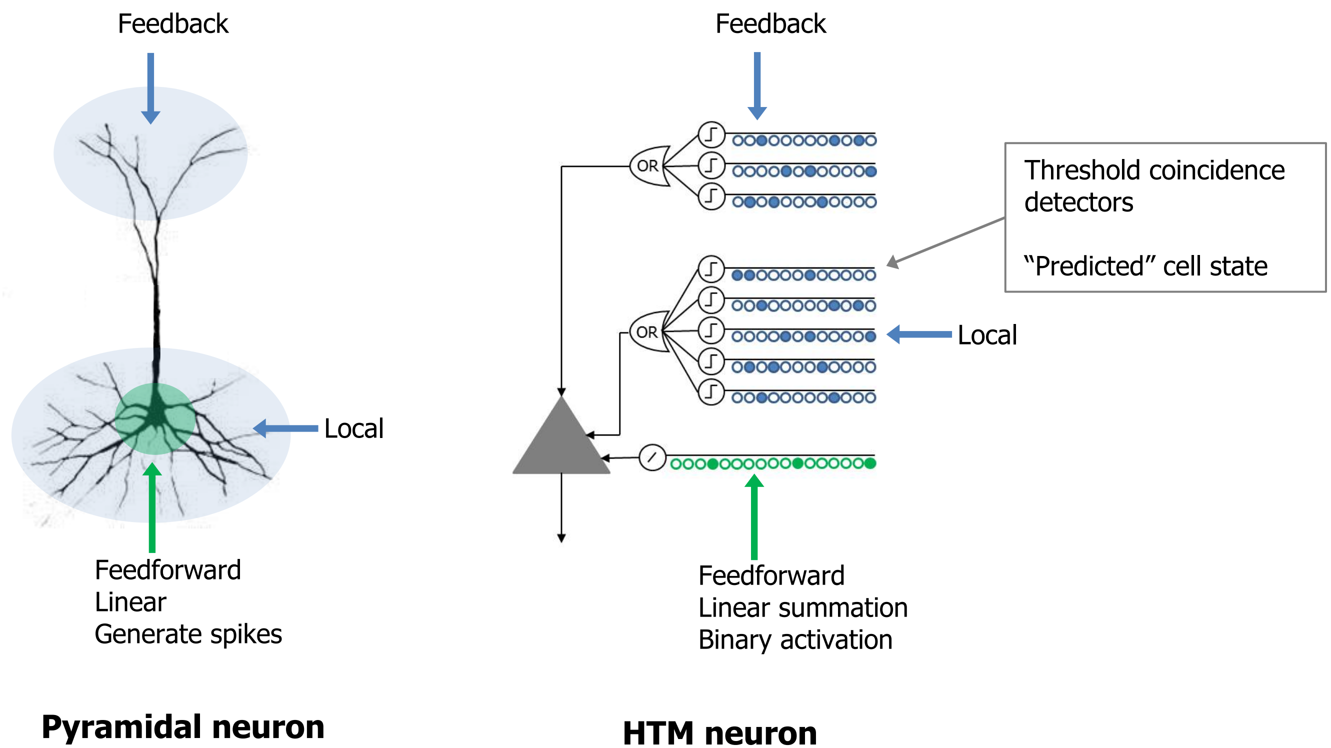
## What Computation do Active Dendrites Perform?

### What computation is essential in cortex?

## Sequence learning



# HTM Neuron Models Proximal and Active Dendrites



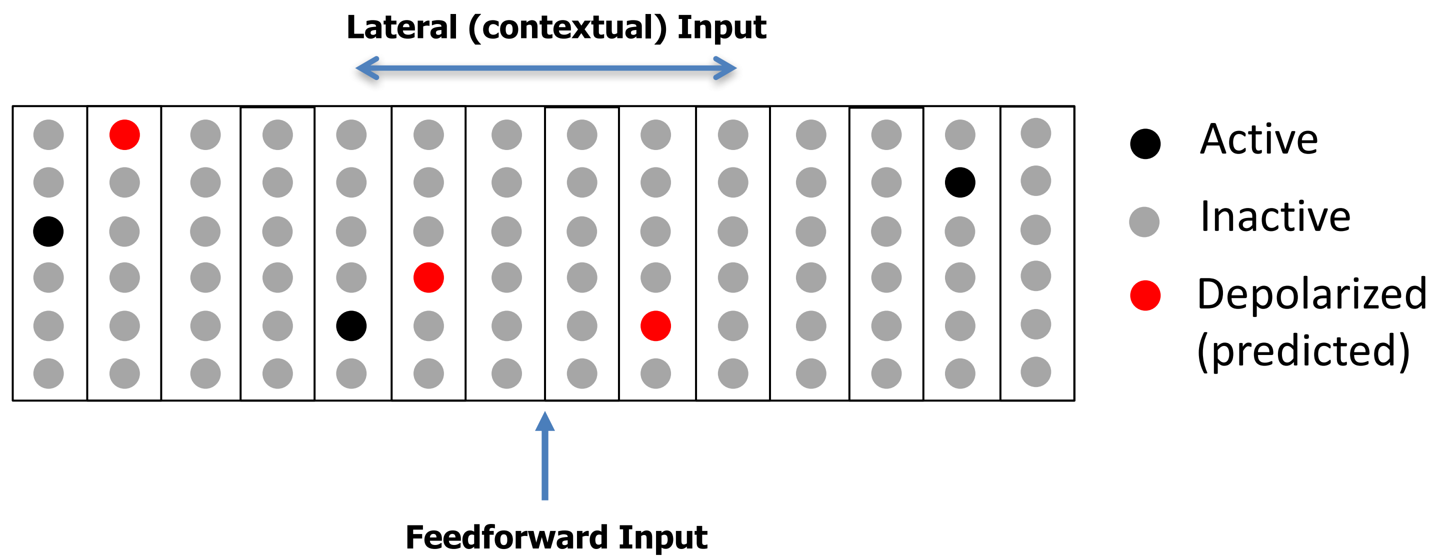

Invokes top-down expectations

Learn transitions between activity patterns

Basic receptive field

Hawkins & Ahmad, Front. Neural Circuits, 2016

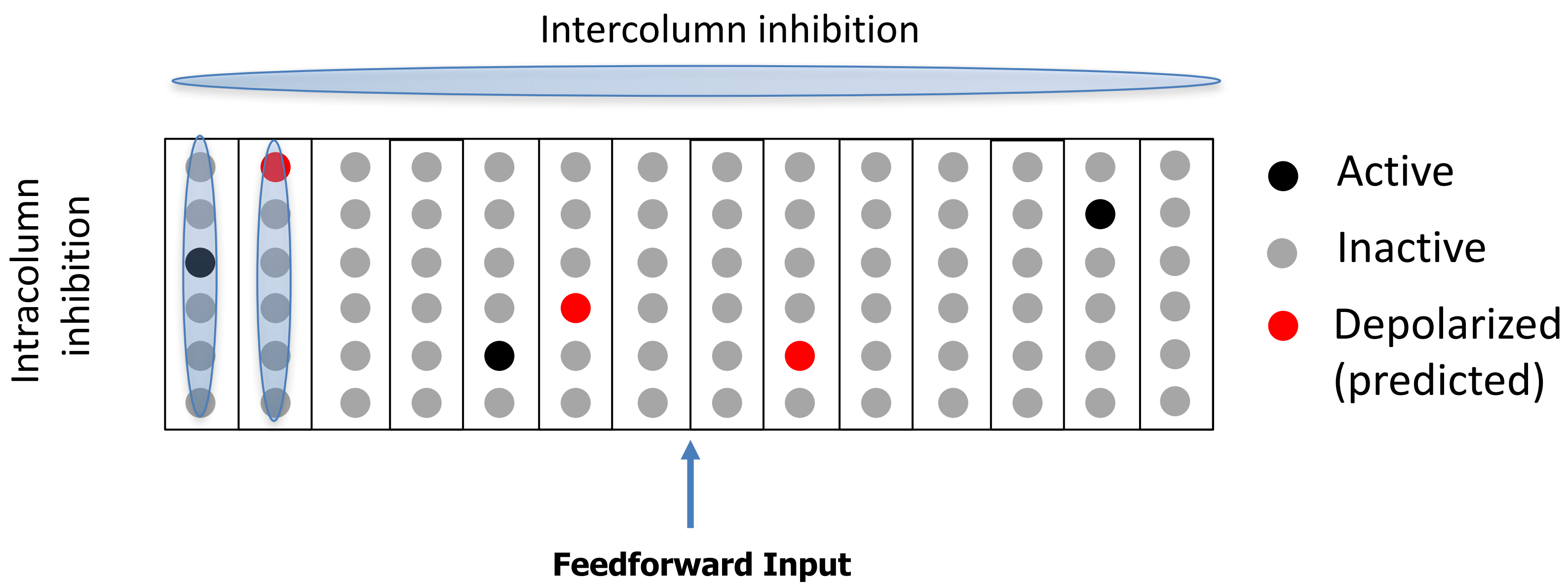
# Network of Neurons with Active Dendrites




Neurons in the same column have the same feedforward connections
Different neurons in the same column has different lateral connections

Feedforward connections onto the proximal dendrites activate neurons directly
Lateral connections onto the basal dendrites depolarize neurons without generating an immediate action potential

# Doubly Sparse Activation due to Two Inhibition Systems



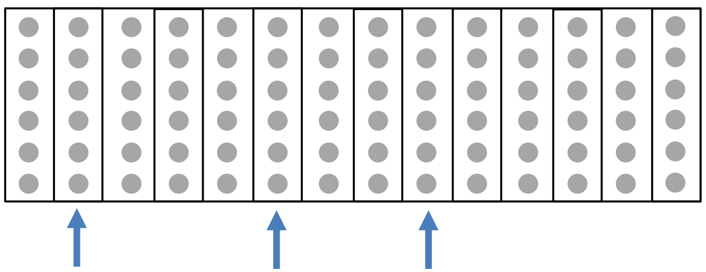

Intercolumn inhibition allows a sparse set of columns to become active

Depolarized cells will fire faster and prevent other cells in the same column from firing through intracolumn inhibition when feedforward input arrives

# Arranging Neurons In Minicolumns Leads To Powerful Sequence Memory & Prediction Algorithm

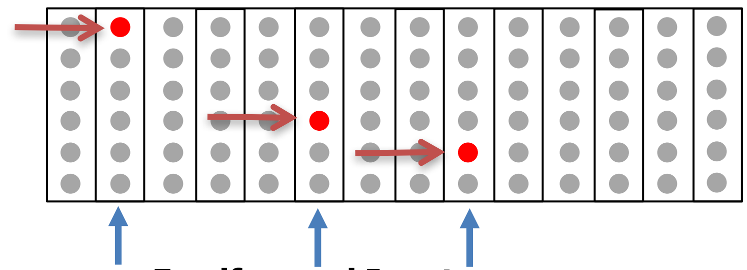
**No prediction**

t-1



**Feedforward Input**
**Sparse activation of columns**
**(intercolumn inhibition)**

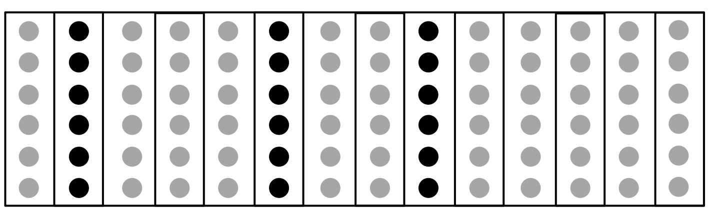
**With prediction**



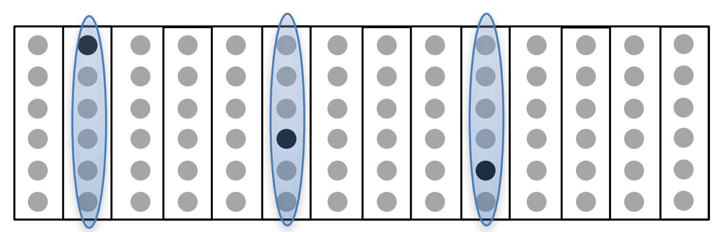
**Feedforward Input**

**A subset of cells are depolarized via predictive contextual input**

t



**No prediction**
**All cells in column become active**
**(surprise/oddball response)**

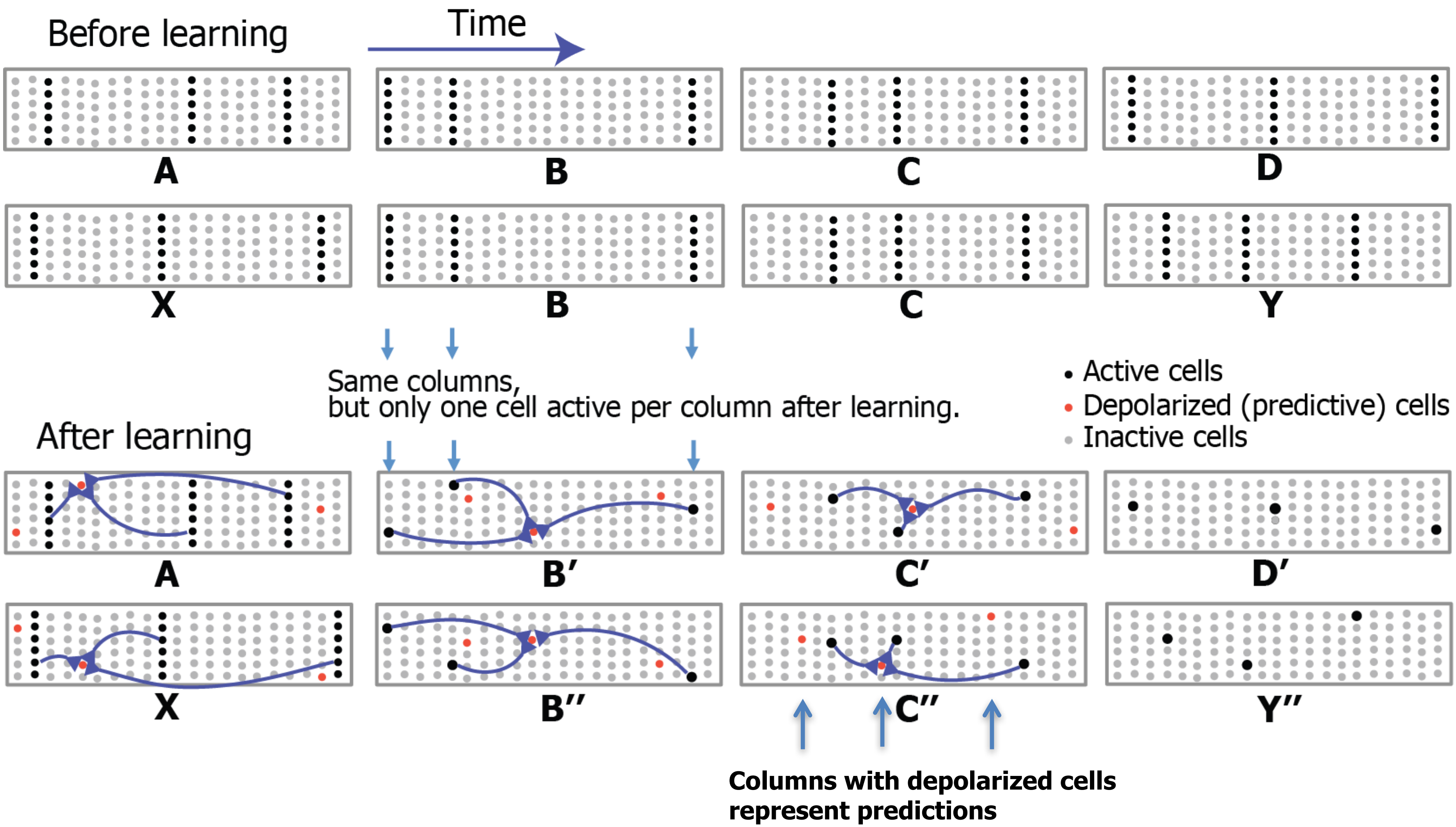


**With prediction**
**Only predicted cells in column become active**
**(stimulus-specific adaptation)**

***Two separate sparse distributed representations***

# High Order Sequences

**Two sequences:** **A-B-C-D** **X-B-C-Y**



# HTM Sequence Memory : Computational Properties

***1) On-line learning***

***2) High-order representations***
For example: sequences “ABCD” vs. “XBCY”

***3) Fully local and unsupervised learning rules***

***4) Extremely robust***
Tolerant to >40% noise and faults (neuron death)

***5) Fast adaptation to changes***

***6) Multiple simultaneous predictions***
For example: “BC” predicts both “D” and “Y”

***7) High capacity***

*Extensively tested, deployed in commercial applications*

*Full source code and documentation available: numenta.org & github.com/numenta*

*Papers available: (*Hawkins & Ahmad, Front. Neural Circuits, 2016; Cui et al., 2015, 2016*)*

# Outline

- Cell assemblies and the HTM Model Neuron
- Network of neurons learn sequences
- Testable predictions of HTM
- Presence of cell assemblies in the mouse visual cortex

# Testable Predictions

1) Presence of cell assemblies in the cortex with natural stimulus

2) Sparser activations during a predictable sensory stream. (Vinje & Gallant, 2002)

3) Unanticipated inputs leads to a burst of activity correlated vertically within mini-columns.

4) Neighboring mini-columns will not be correlated. (Ecker et al, 2010)

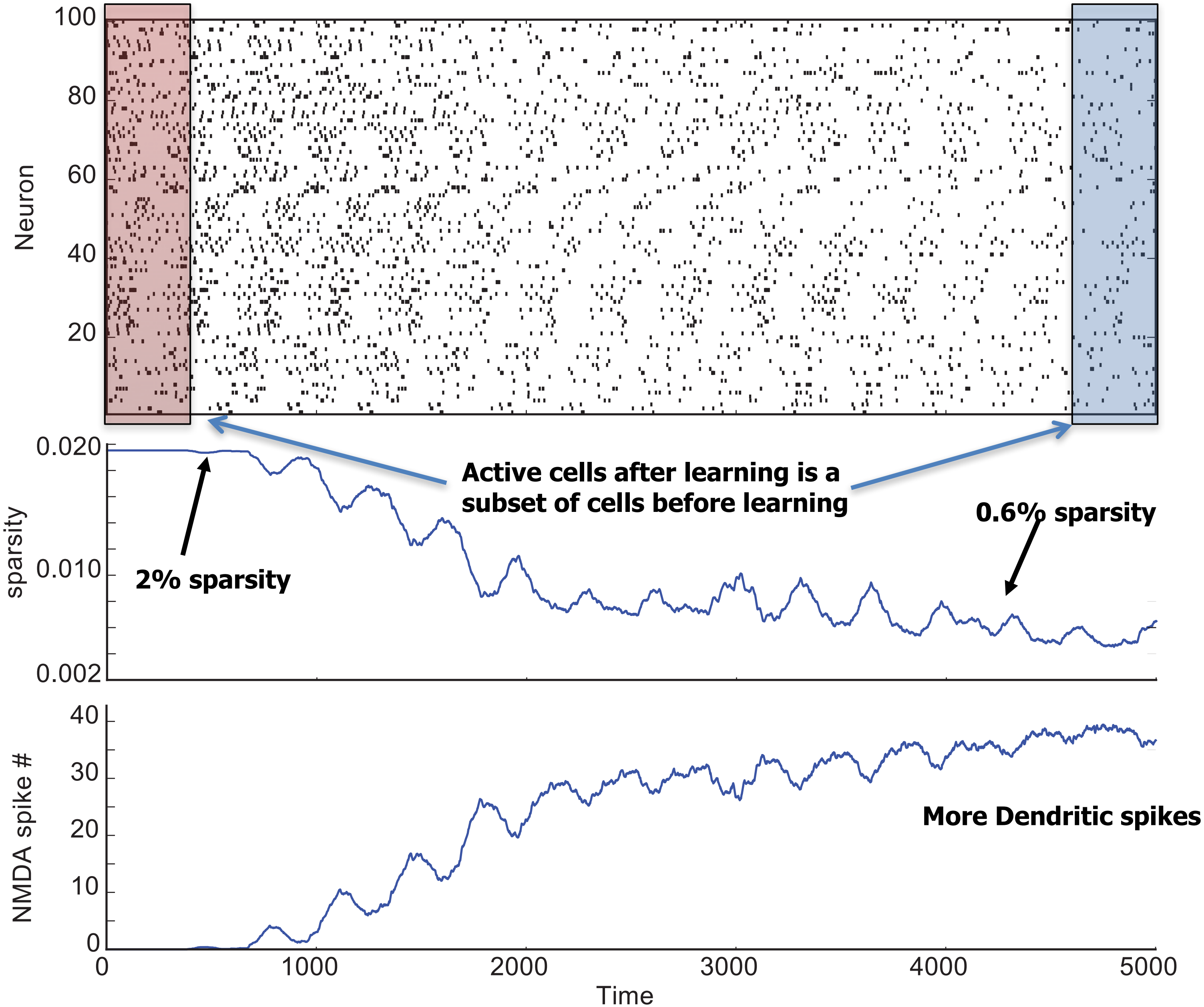
5) Predicted cells need fast inhibition to inhibit nearby cells within mini-column.

Plasticity & Learning:
7) Localized synaptic plasticity for dendritic segments that have spiked followed a short time later by a back action potential. (Losonczy et al, 2008)

8) The existence of localized weak LTD when an NMDA spike is not followed by an action potential.

9) The existence of sub-threshold LTP (in the absence of NMDA spikes) in dendritic segments if a cluster of synapses become active followed by a bAP.

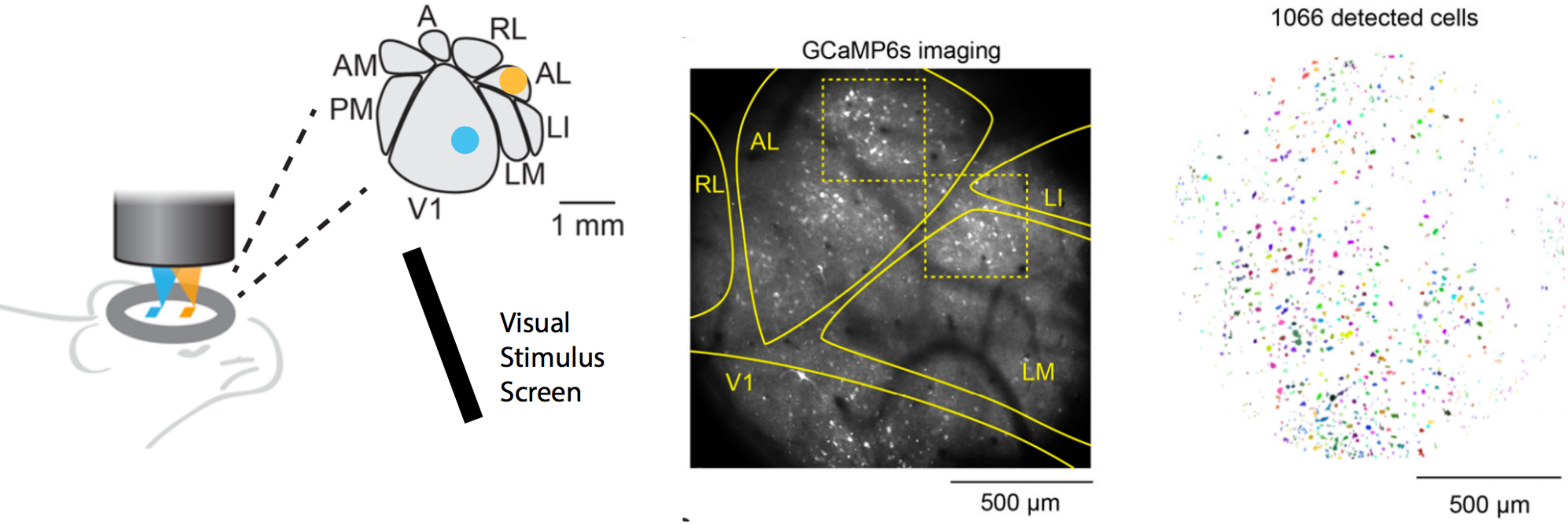
# HTM: Sparse Activity Becomes Sparser For Learned Sequences



# Data

- Simultaneous 2-photon calcium imaging from V1 and AL

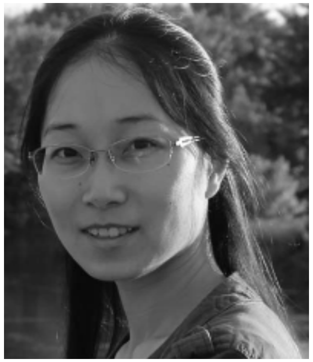
Spencer Smith




Stirman et al. 2016, Nature Biotechnology

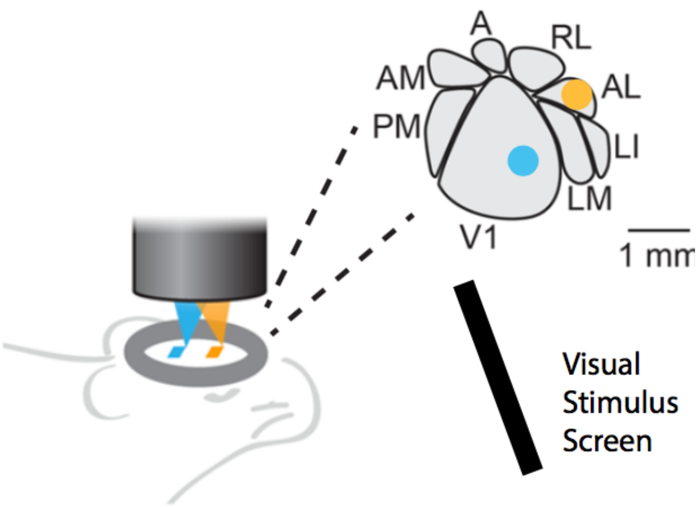
# Visual Stimulus

30 seconds naturalistic stimuli, 20 repeats

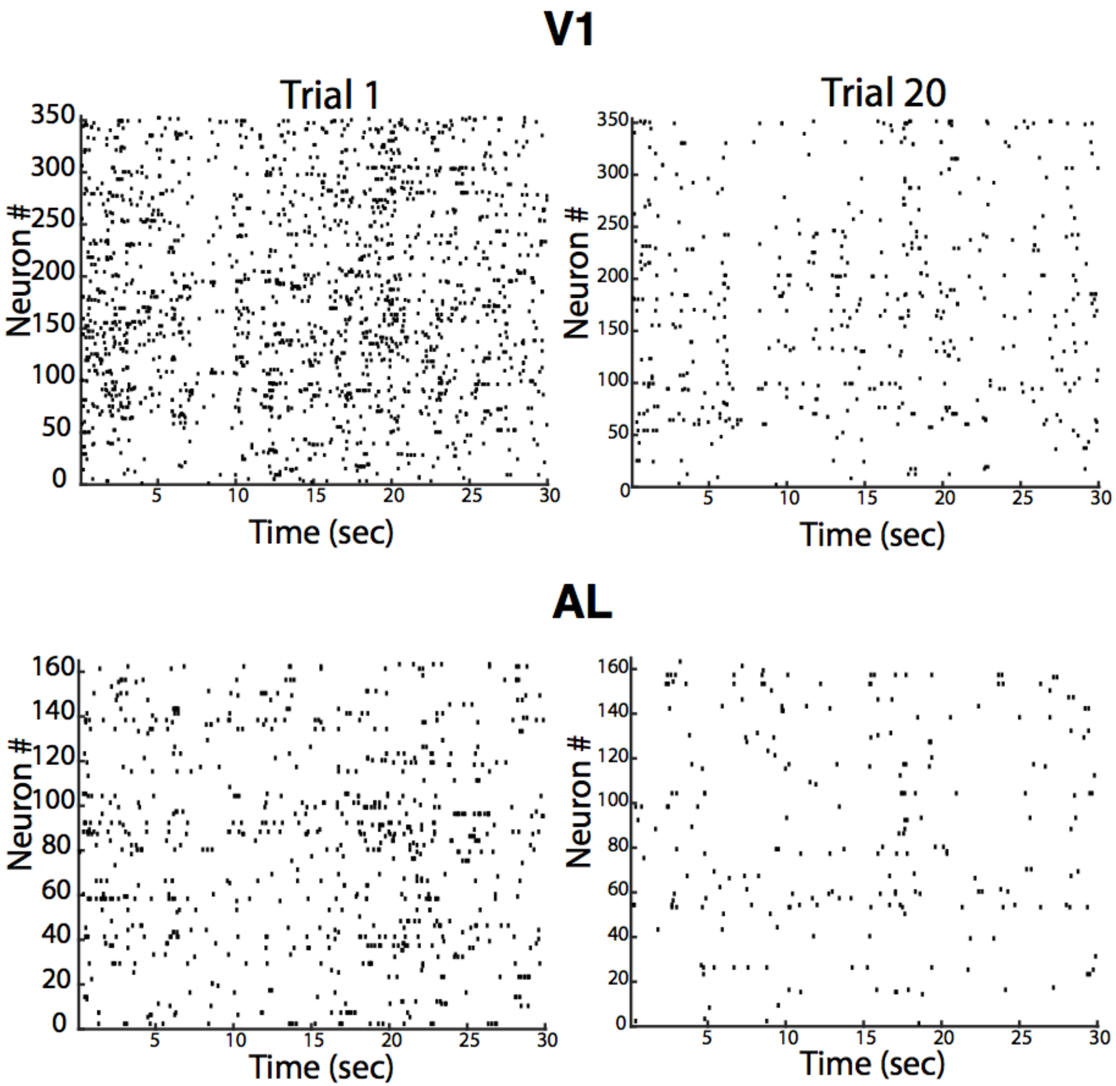


Yiyi, Yu

# Experiment

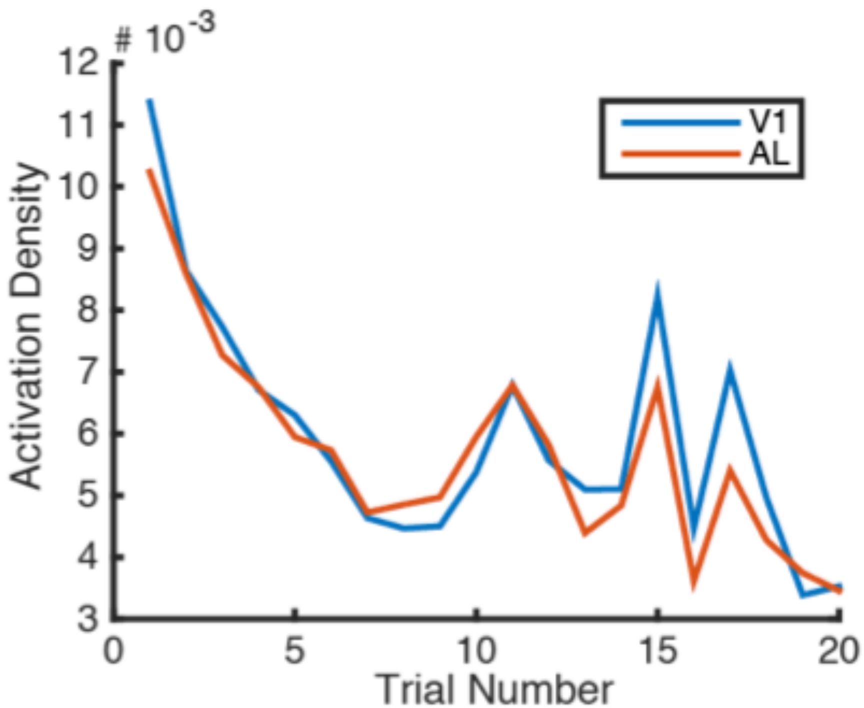



Population response



# Result 1: Increasing sparsity across repeats

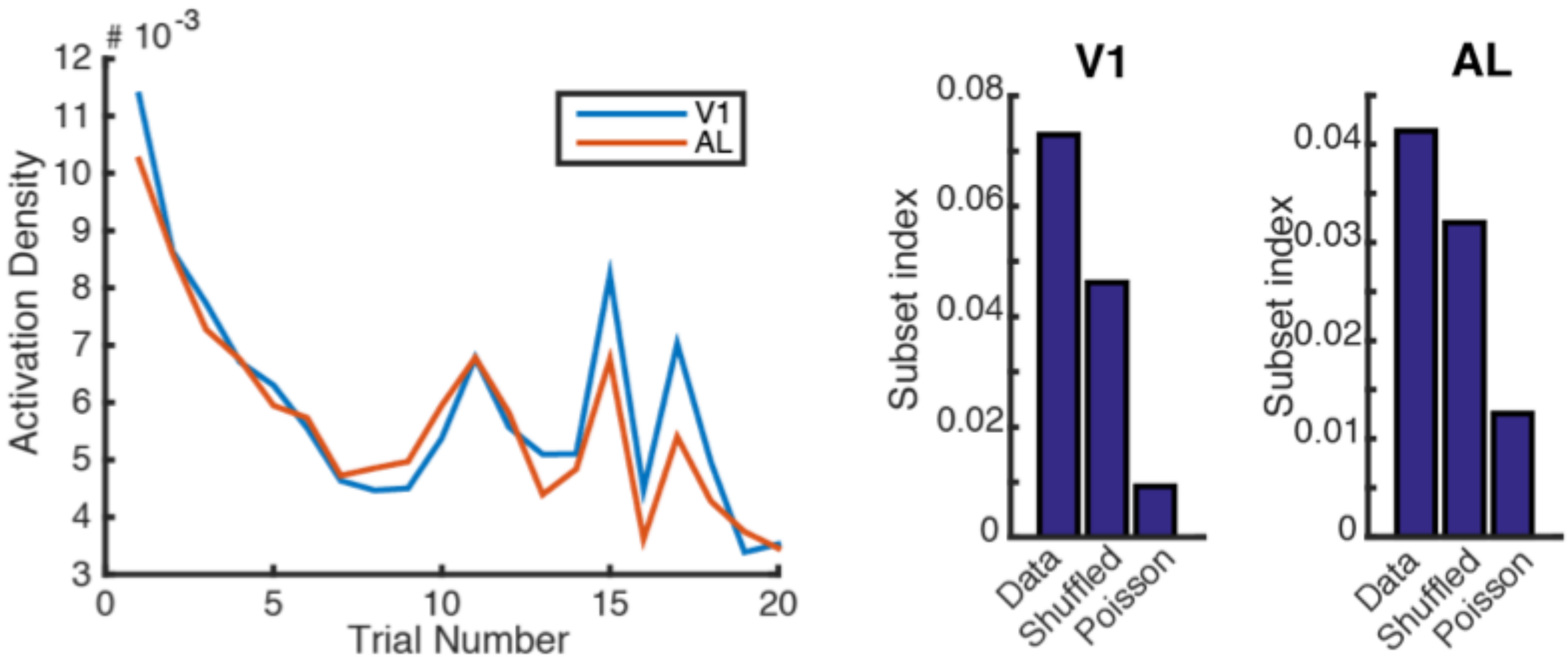
- Sparsity: 1% → 0.4%



## Result 1: Increasing sparsity across repeats

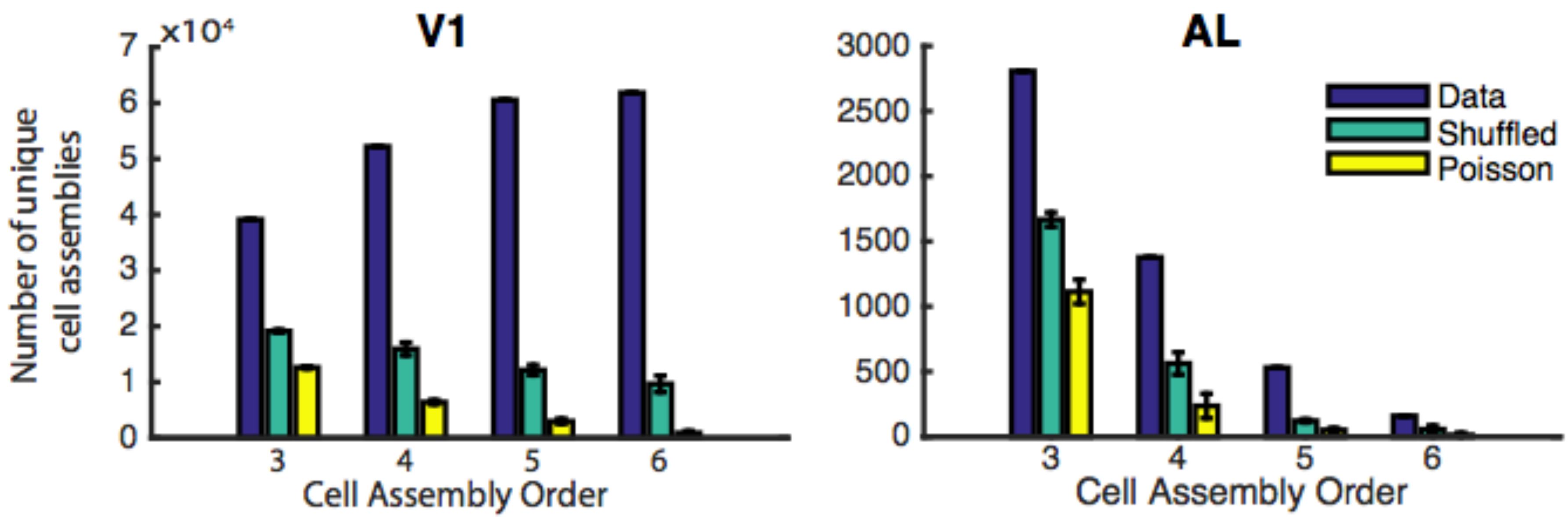
- *Subset Index:* $\dfrac{\text{\# cells active on both the first and the last trial}}{\text{\# cells active on the last trial}}$

  - Sparsity: 1% → 0.4%



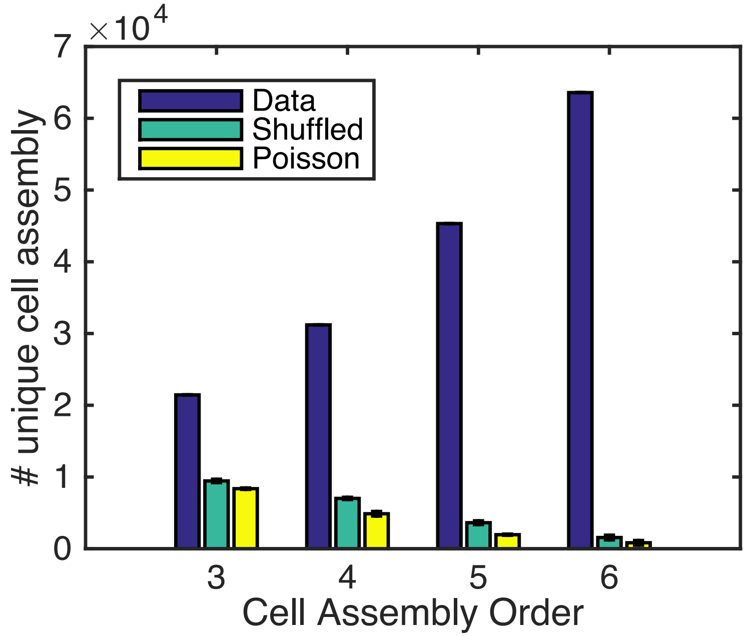
# Result 2: Presence of high-order cell assemblies

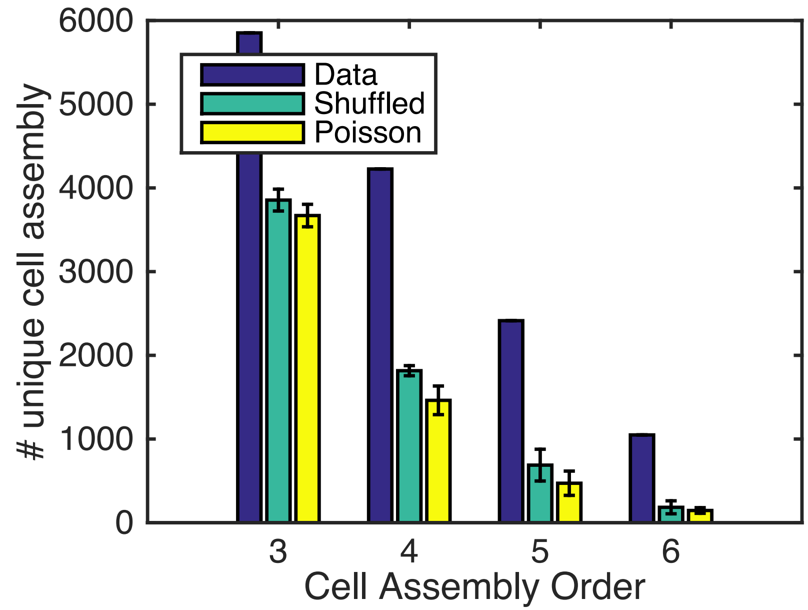
- *k*-cell assembly: a set of *k* cells that are coactive together (<75 ms) at least once.
- Method: Enumerate the number of distinct k-cell assemblies (352x8520)
- Cell assemblies occurs more frequently than predicted by the surrogate models, the difference is larger for higher-order patterns

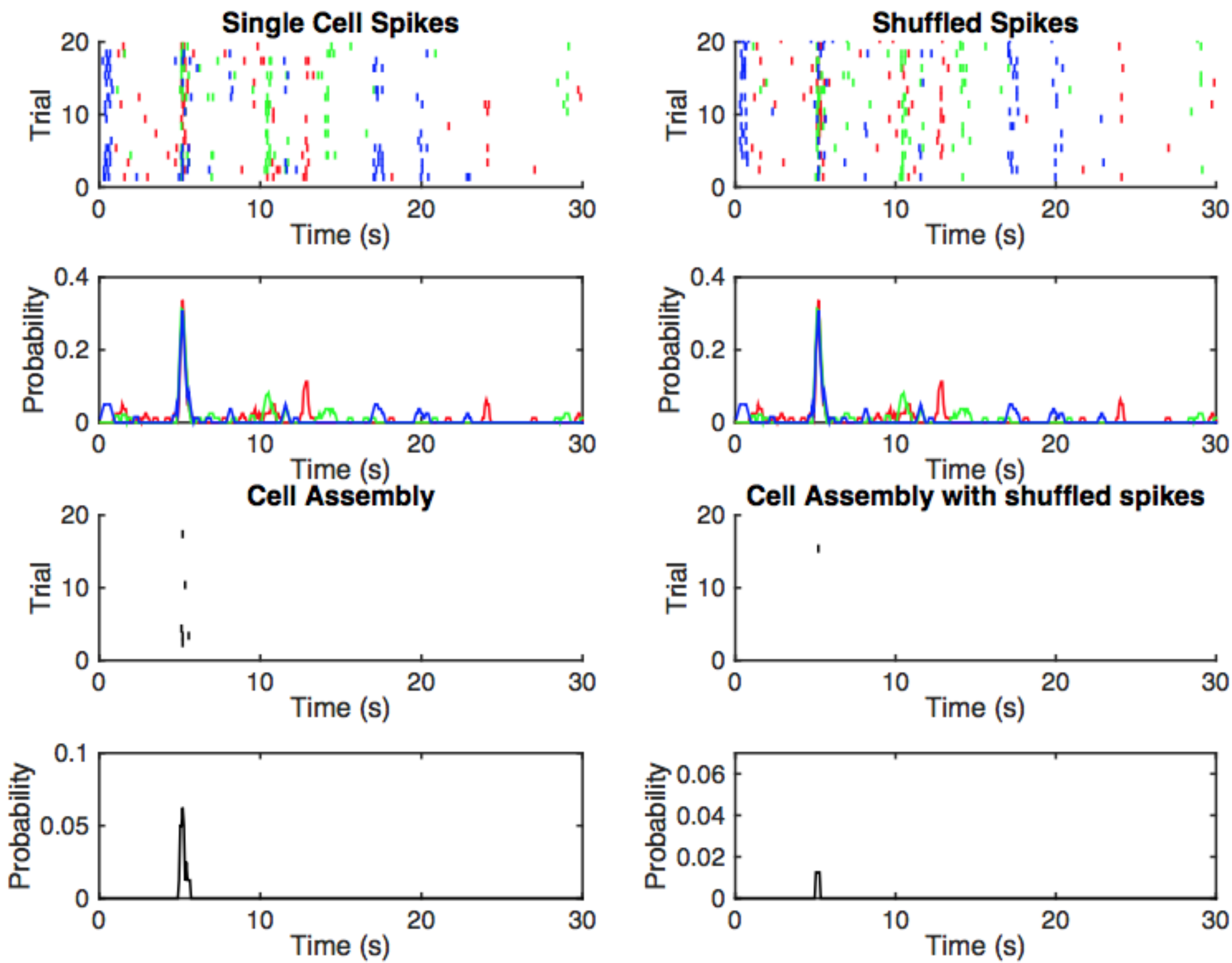



*Poisson model* assumes each neuron fires with a homogeneous firing rate
*Shuffled model* shuffles spikes across repeats for individual neurons, it preserves all the stimulus driven responses, but destroys non-stimulus driven correlations.

# Result 2: Presence of high-order cell assemblies

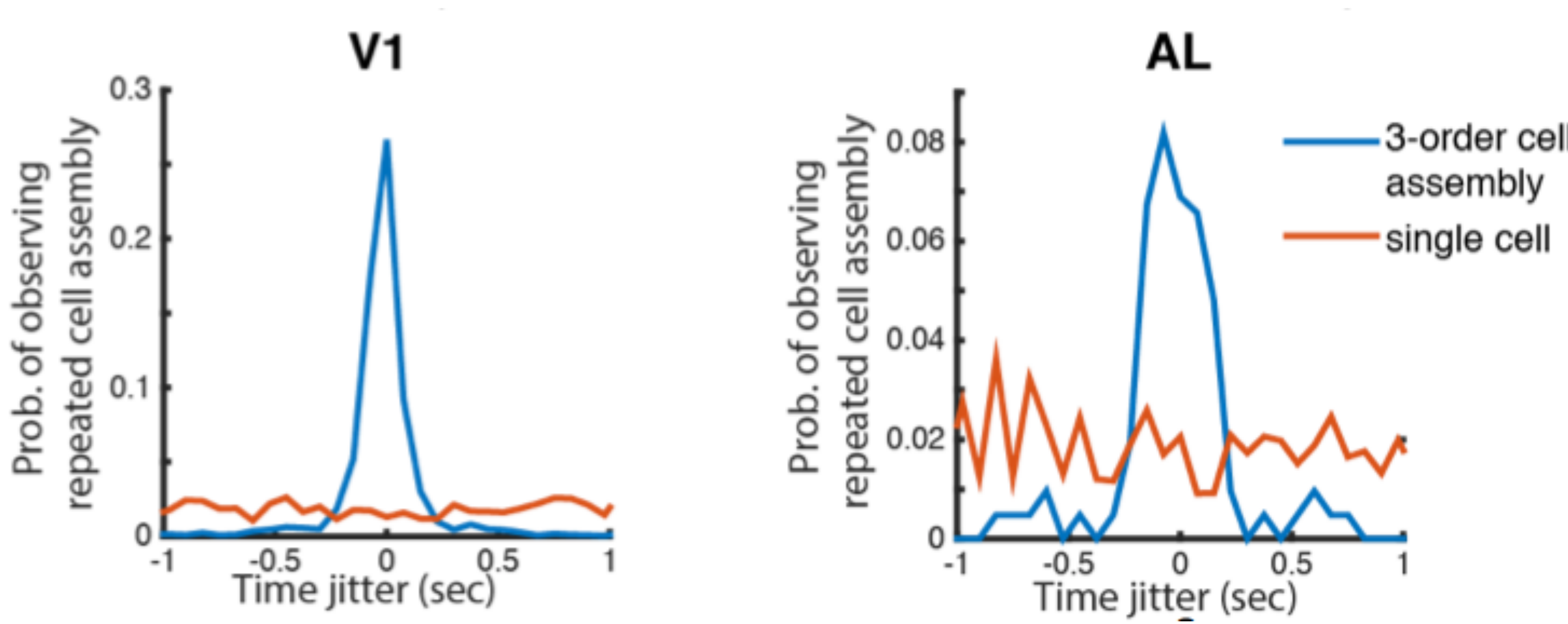



Single Cell Spikes
Shuffled Spikes
Trial
Time (s)
Probability
Cell Assembly
Cell Assembly with shuffled spikes

# Result 3: Cell Assemblies are locked to visual stimulus

- *Distribution of cell assembly occurrence times relative to the median occurrence time*



# Summary

**Model**

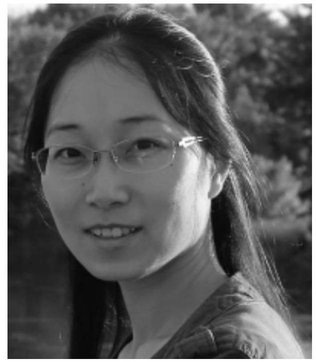
- Networks of neurons with active dendrite forms a powerful sequence learning algorithm.
- Active dendrite requires repeatable cell assemblies in a neural population.

**Data**

- Repeatable cell assemblies are found in mouse visual cortex during natural movie stimulation.
- Cell assemblies cannot be explained by stimulus response properties of individual neurons.

## Collaborators

Spencer Smith



Yiyi, Yu

Subutai Ahmad

Jeff Hawkins

## Contact info:

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