Embedding and Predicting Neural Dynamics

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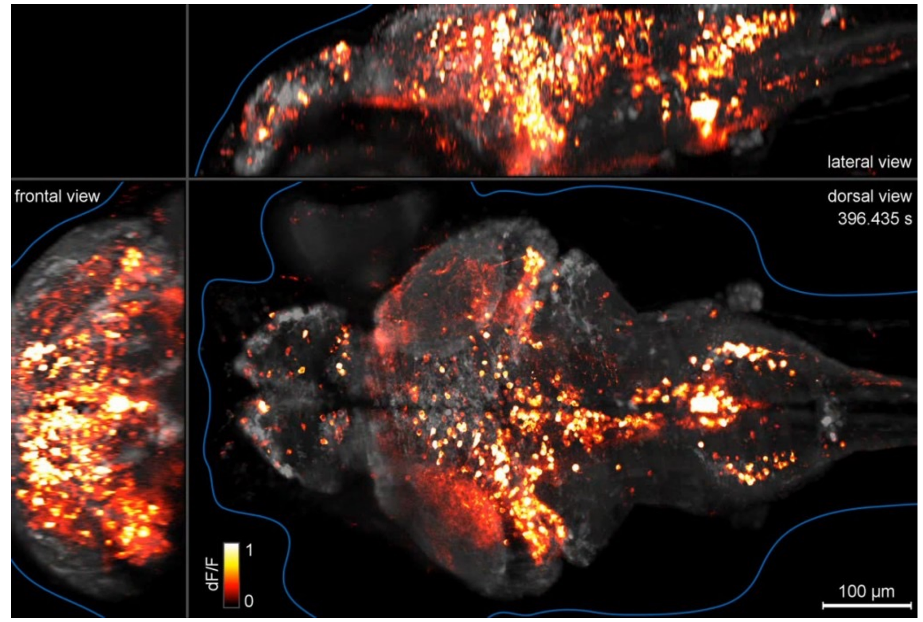
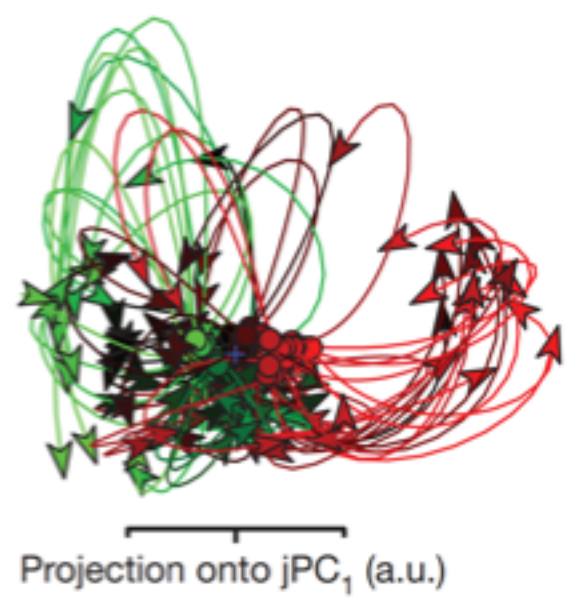
Recording technology has been advanced.



Ahrens and Keller 2013

Yet, the data complexity and nonlinearity challenge our understanding.

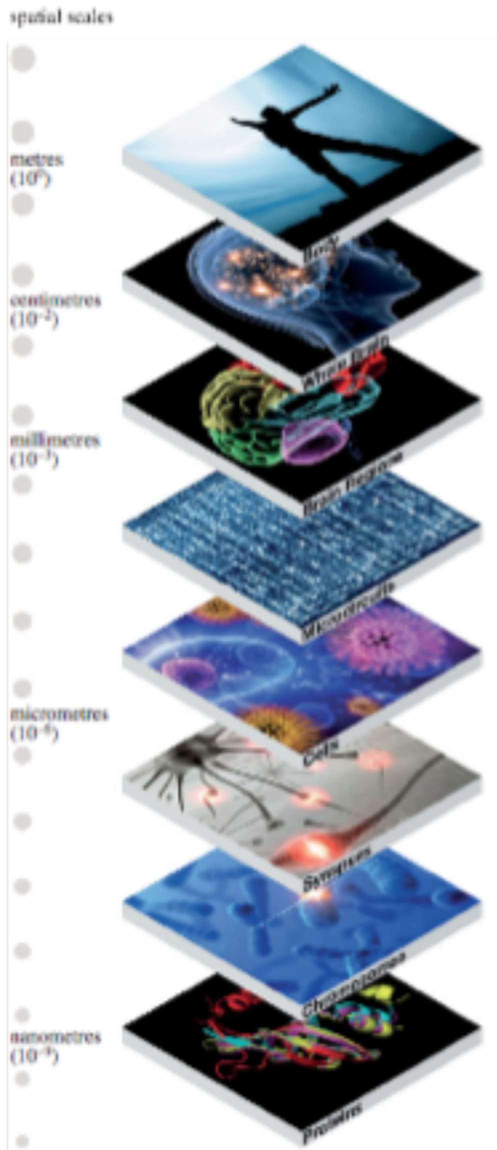


Churchland et al. 2012

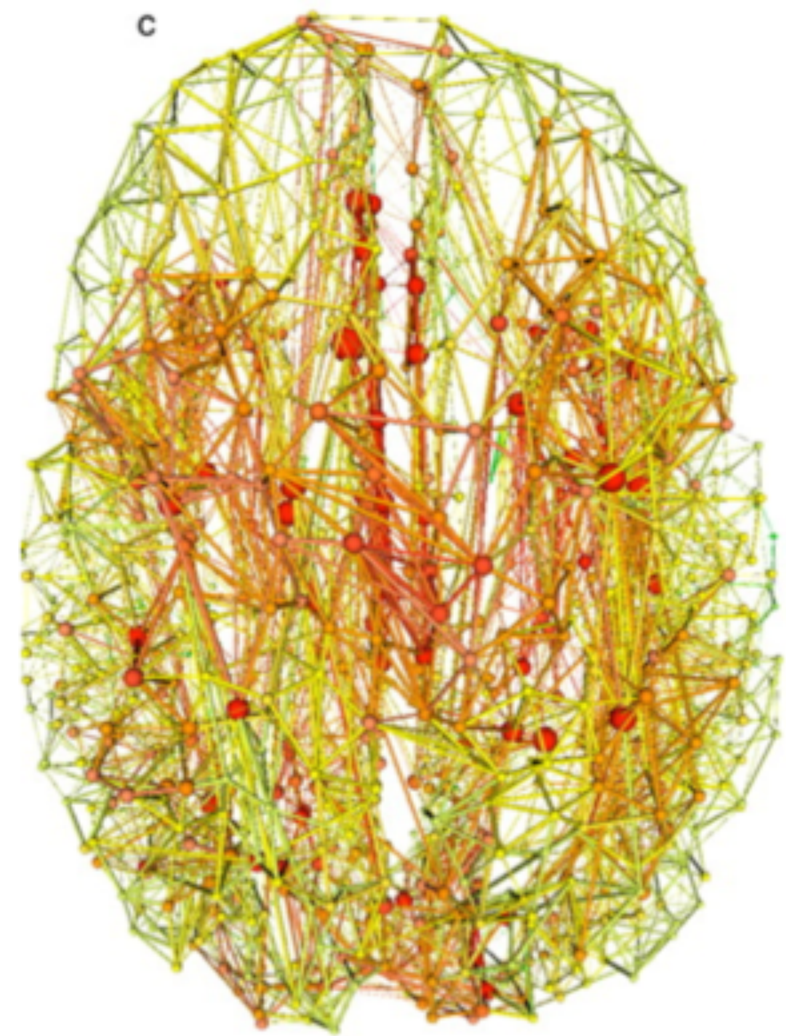
In some cases, the complexity may be an irreducible feature.
Data-based nonlinear analyses would be helpful.

Problems:

- How the *macroscopic dynamics* are related to *microscopic dynamics*?
    - What are *network structures* that mediate this relation?



Frackowiak et al. 2015



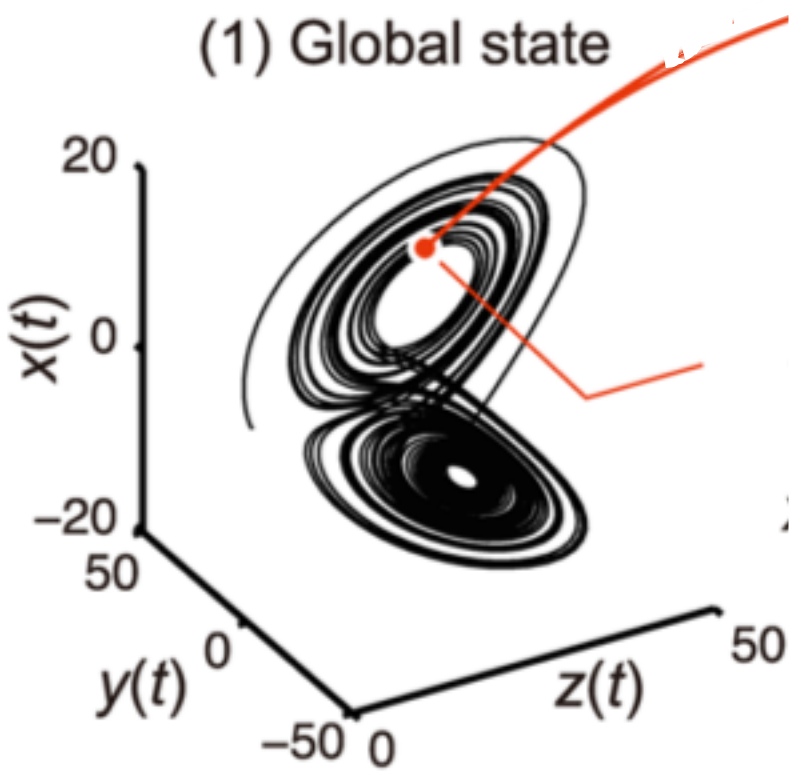
van den Heuvel and Sporns 2011

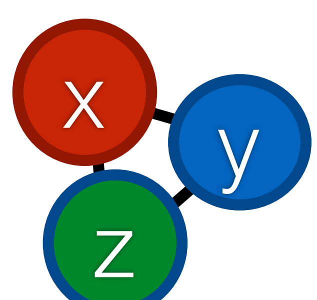
We apply a data-based nonlinear method that can find the links between macro- and microscopic dynamics and extract relevant network features.

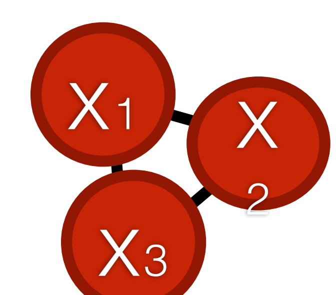
Theory

Delay embedding
— a principle in deterministic dynamical systems —

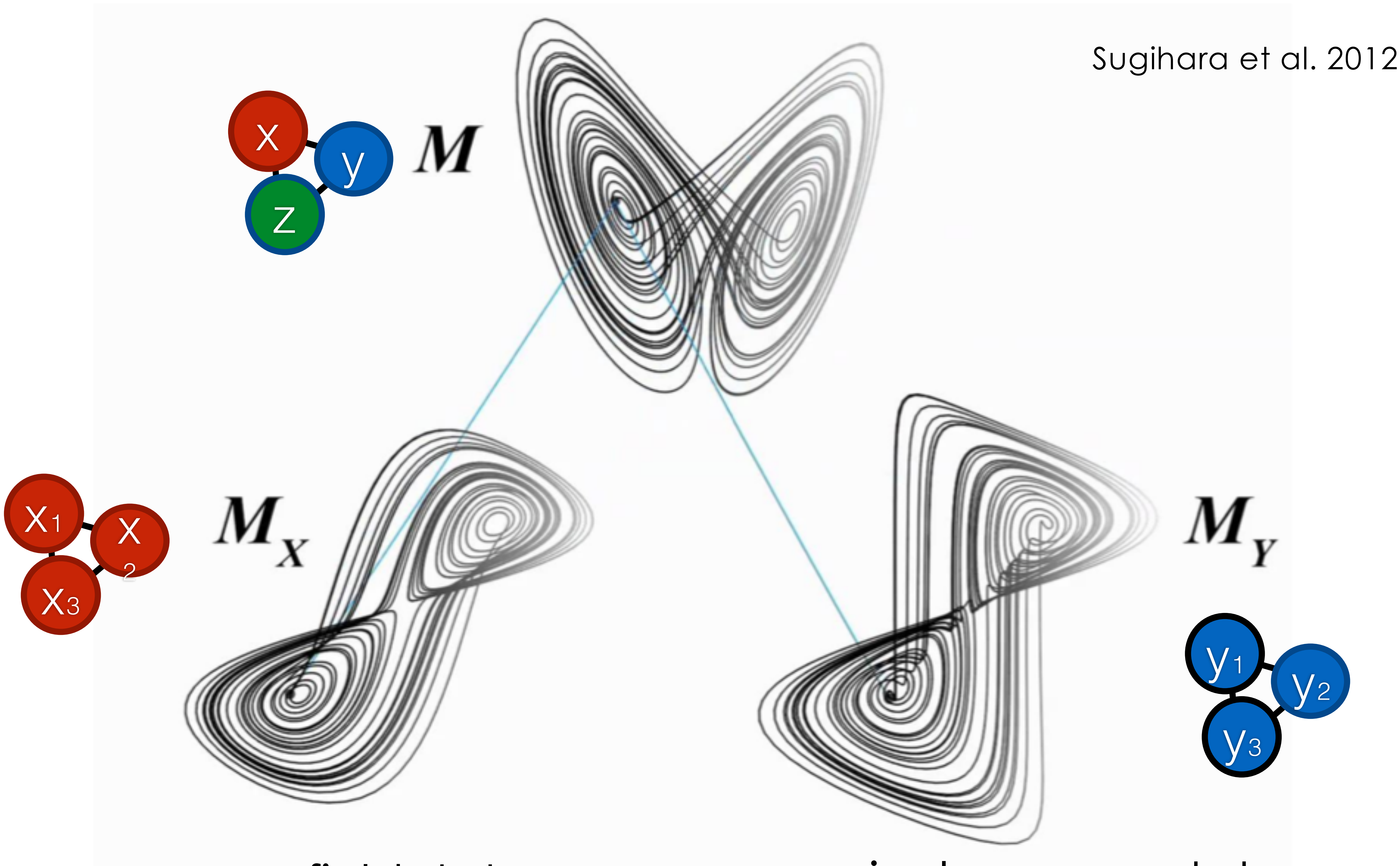
The Takens embedding theorem guarantees a mapping with one-to-one correspondence between a global state and a coupled local state in delay-coordinates (with enough dimensions).







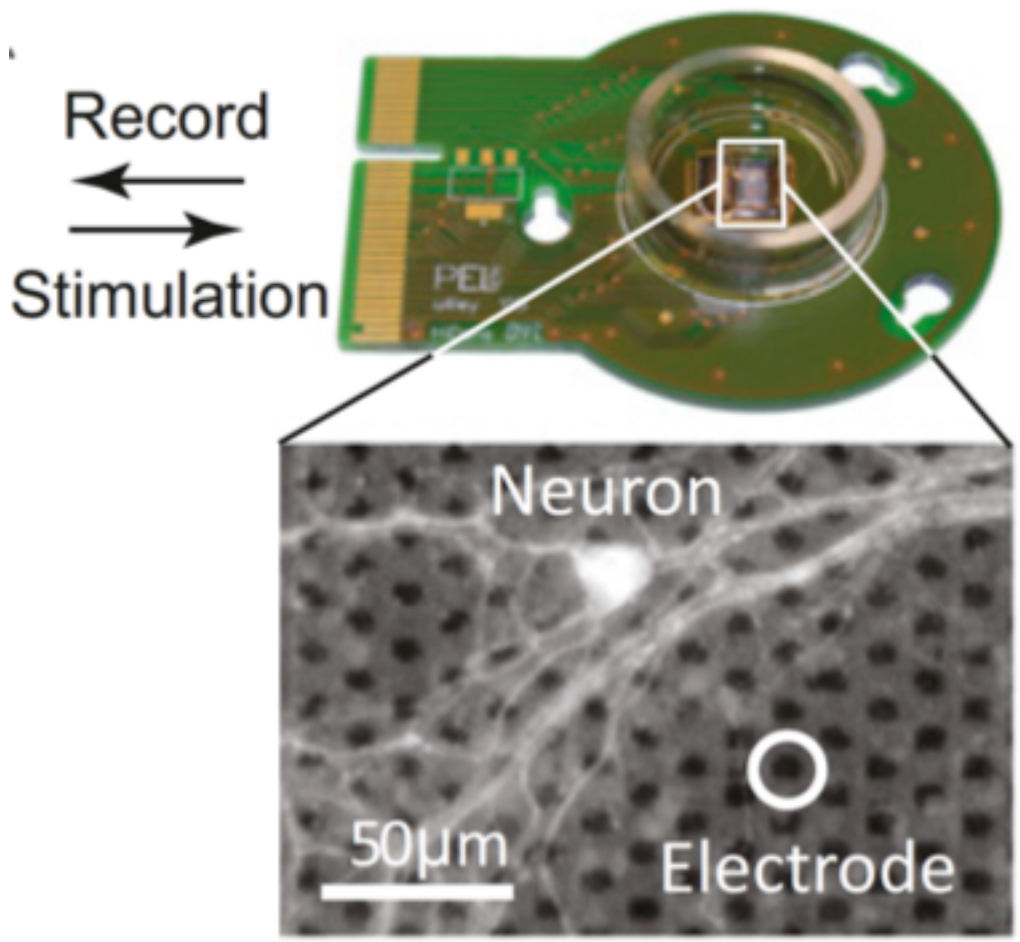
Cross Convergent Mapping:
One-to-one mapping between two interacting local delay-states.



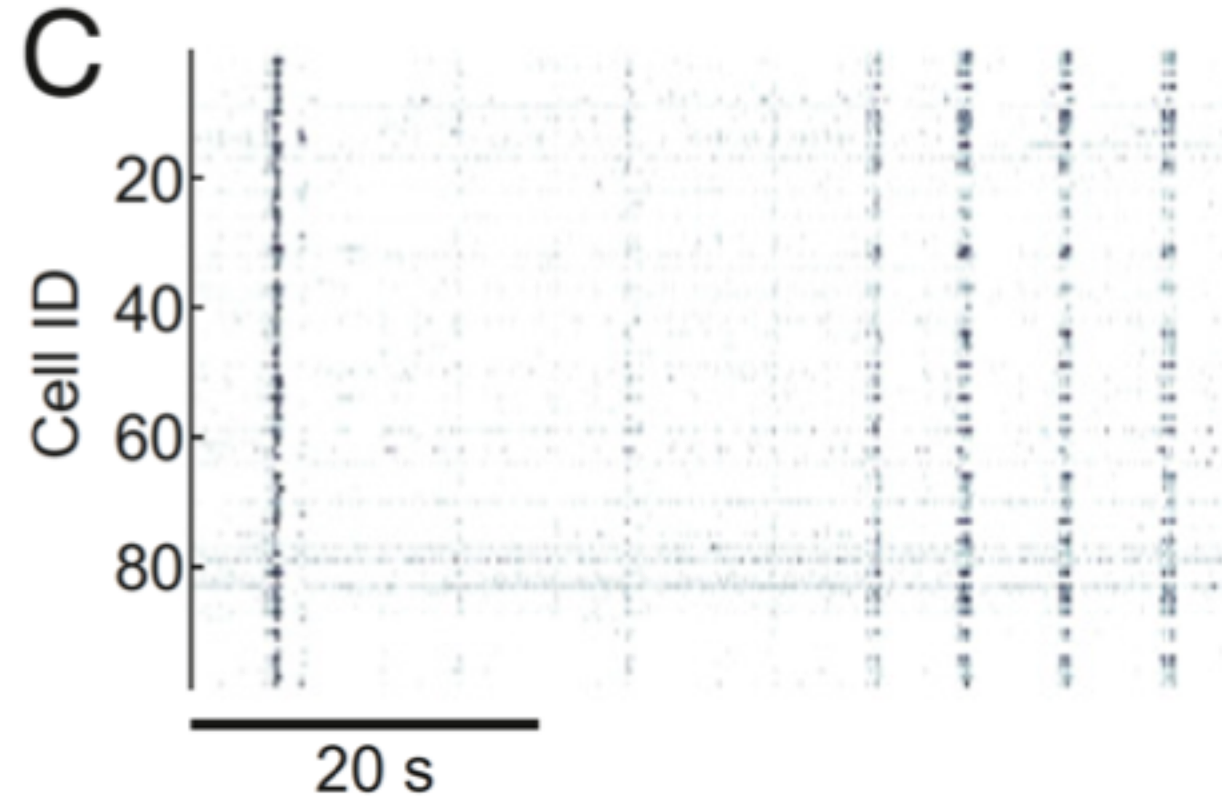
e.g. mean-field state
(macroscopic)

e.g. single-neuron state
(microscopic)

We apply this method to neural population dynamics.



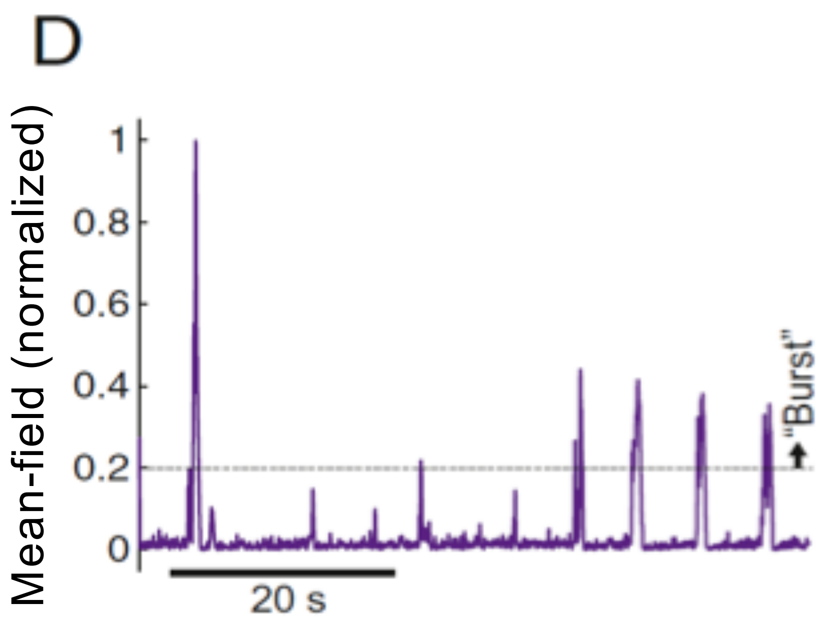
Recordings from cultured neurons.

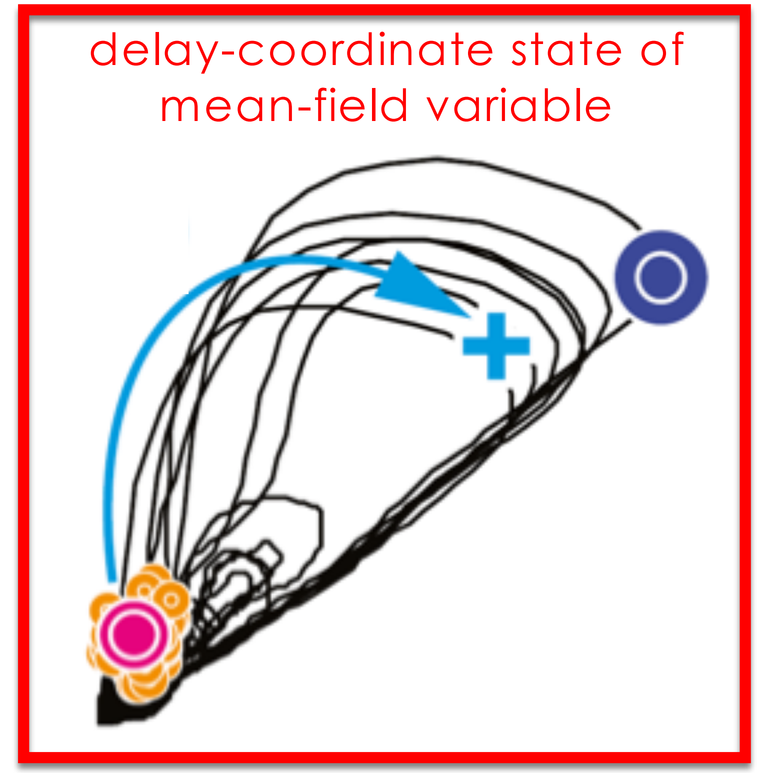


The network spontaneously exhibits bursting.

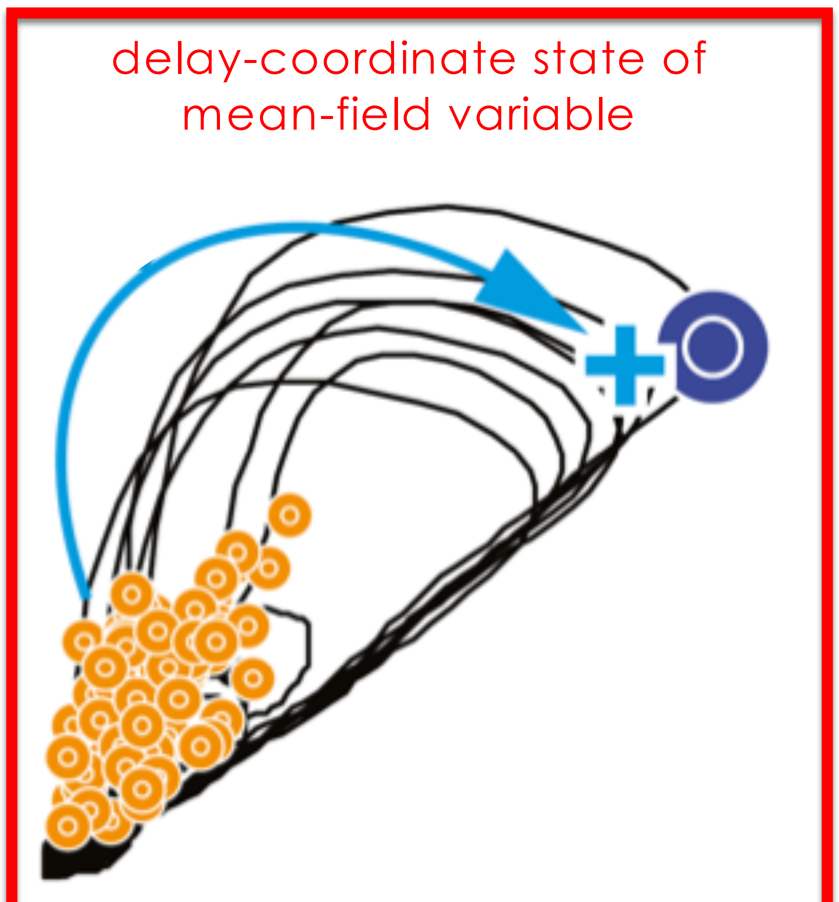
Tajima et al. 2017

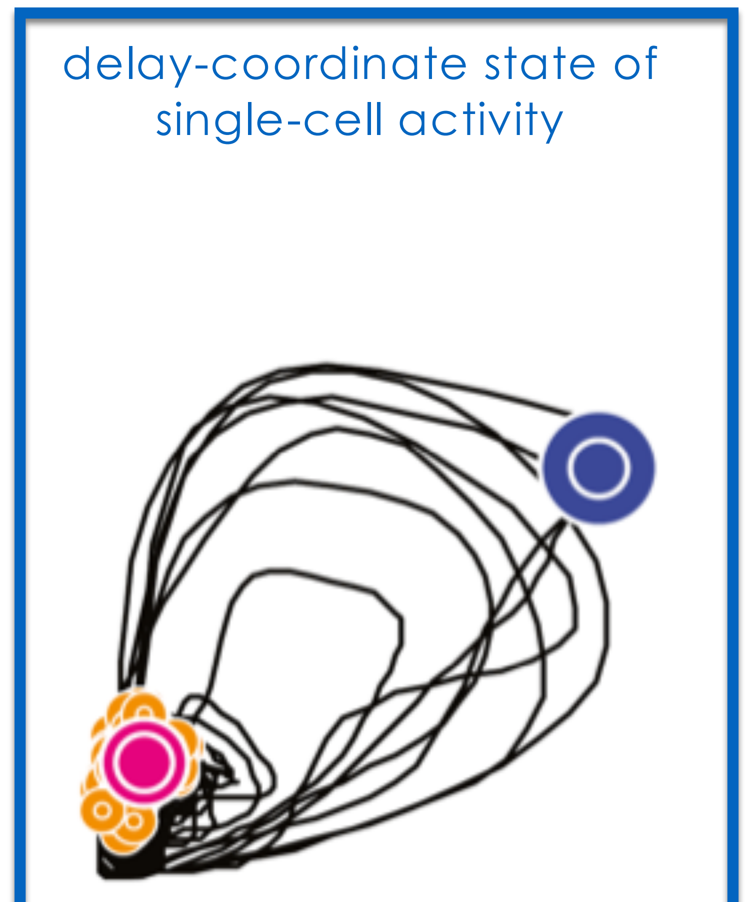
Predicting bursts by the mean-field activity





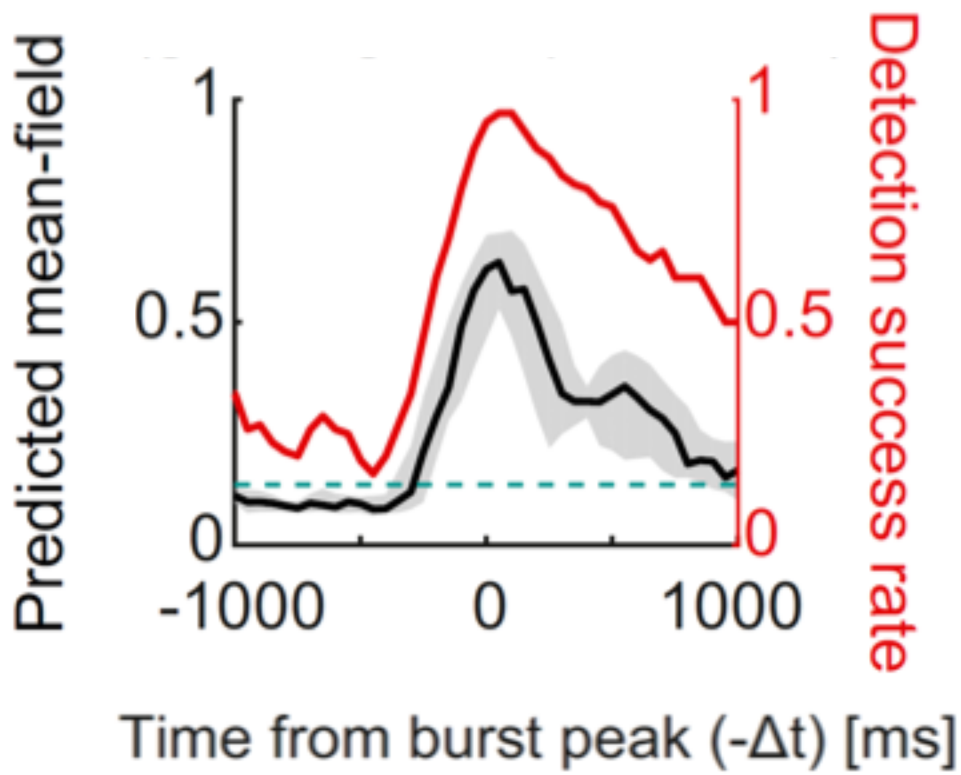
Predicting bursts by a single-neuron activity



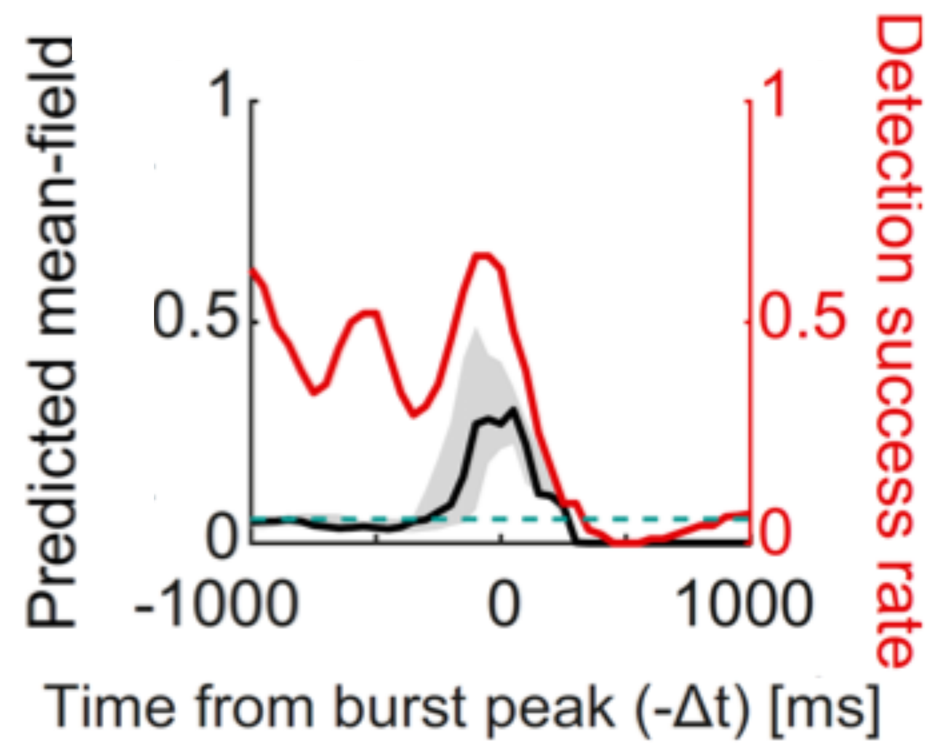


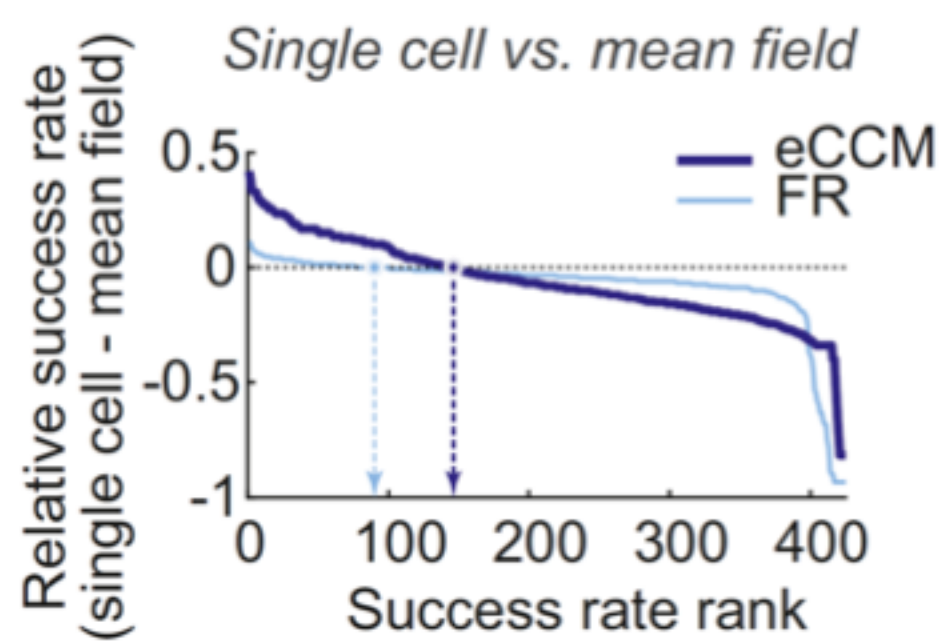
Nonlinear forecasting of burst events

prediction by mean-field state



prediction by single-cell state





About 1/3 of single neurons can forecast bursting more accurately than the mean-field variable.

What is special about the informative neurons?

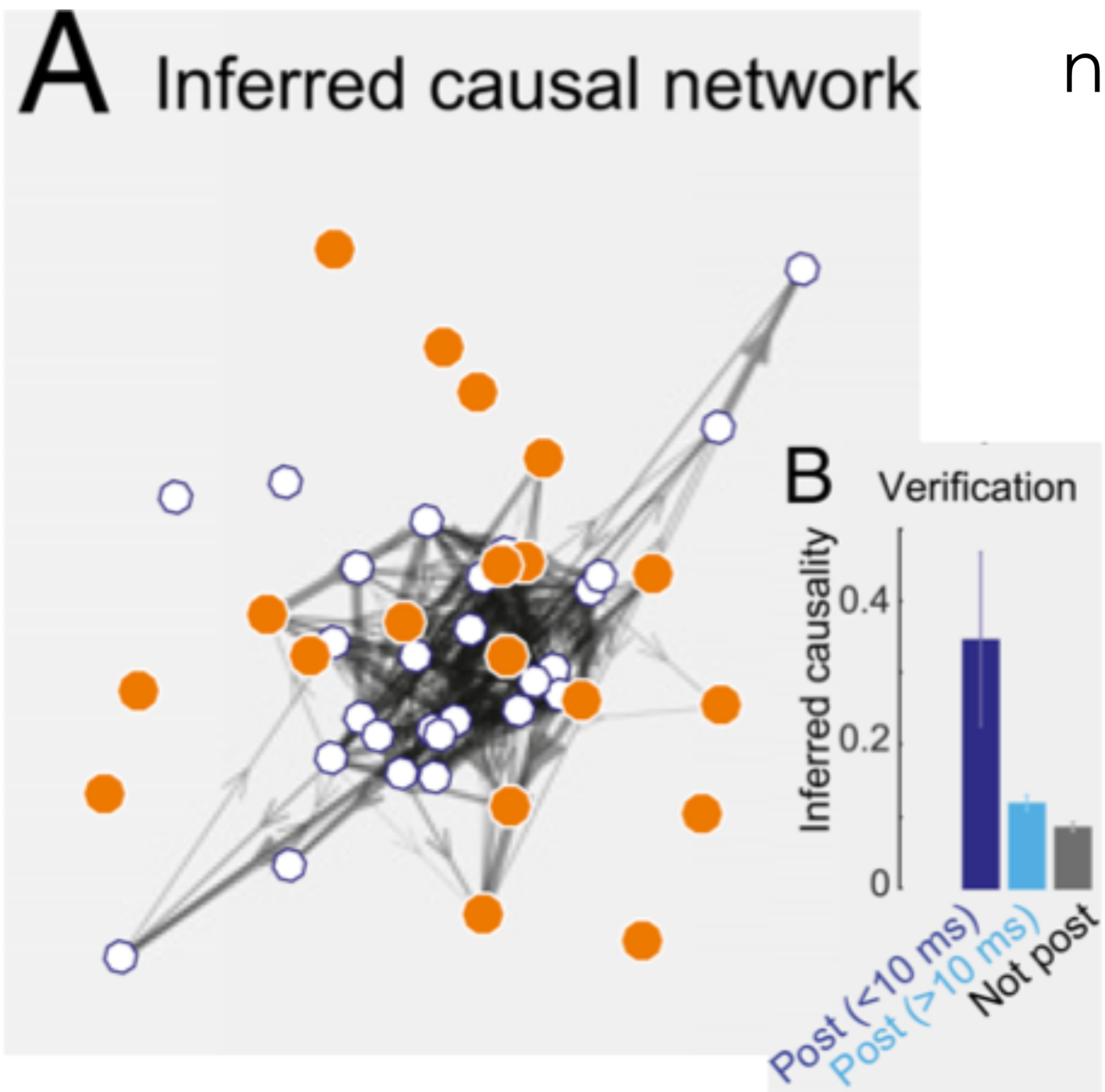
We infer the causal network structure from the non-bursting data and study features specific to these informative neurons.

Causal network inference by cross-embedding

Sugihara et al. 2012

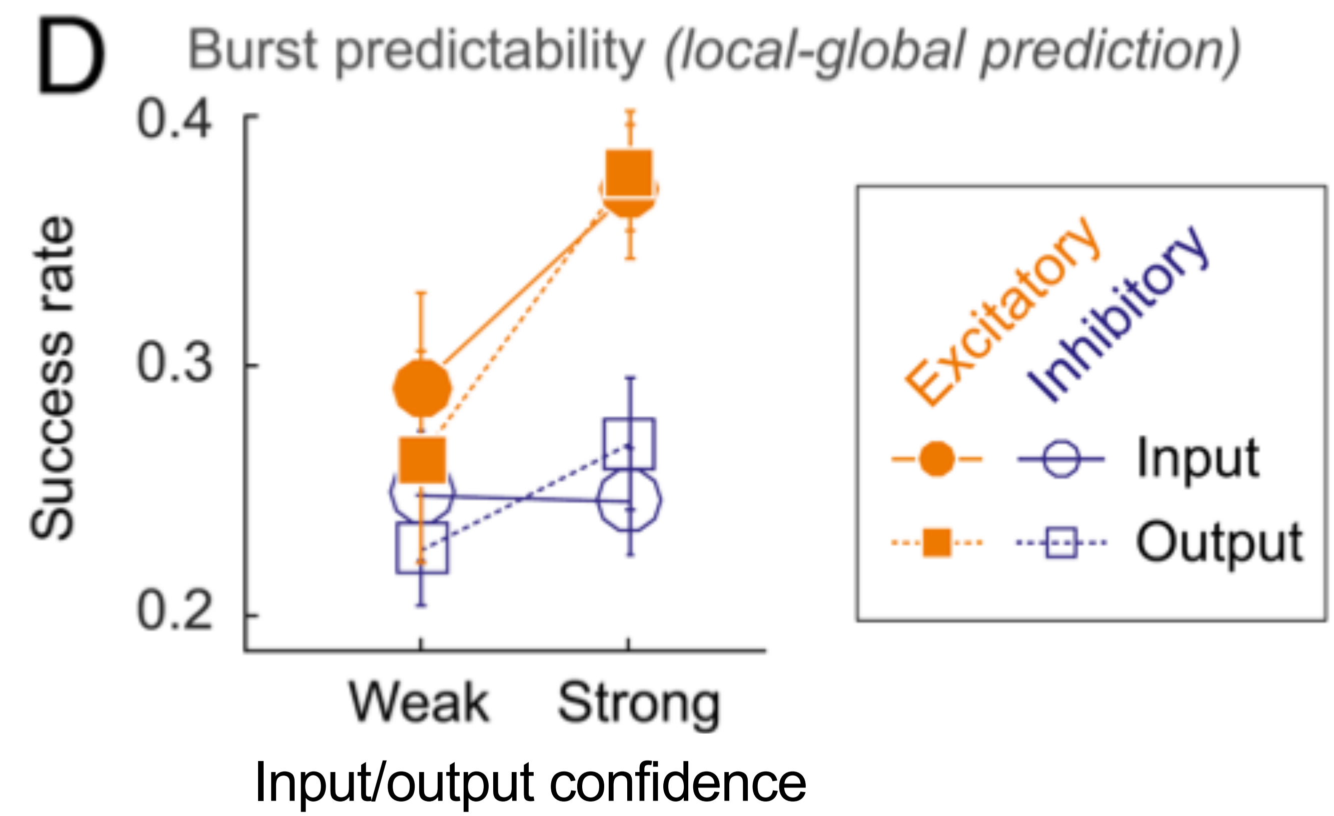
Generically, the state of the upstream node is completely specified by the observation of the downstream node.

We applied the embedding method to non-bursting data.



A subset of inferred causality was experimentally vilified.

Excitatory neurons with strong network interactions predicted bursts.



Summary

- By applying the embedding method, we have extracted deterministic signatures of upcoming macroscopic bursts.
- A single-cell state in delay coordinates is equally or even more informative than the mean-field state for forecasting bursts.
- The intercell variability in the burst predictability reflects the network structure realized during non-bursting periods.

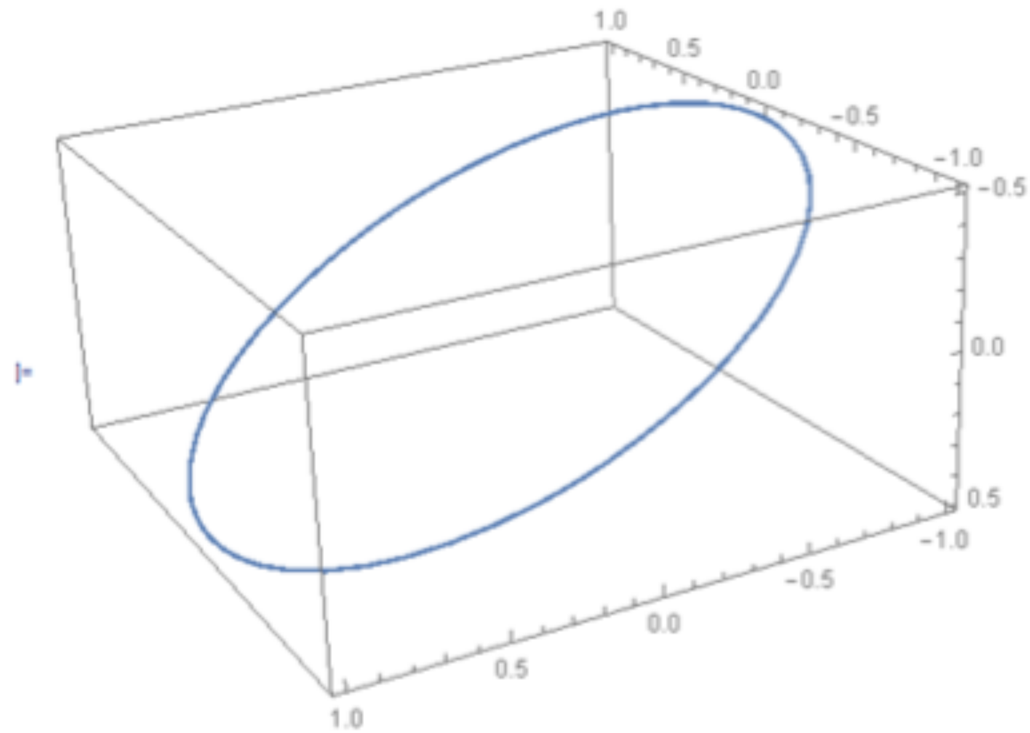
Complexity

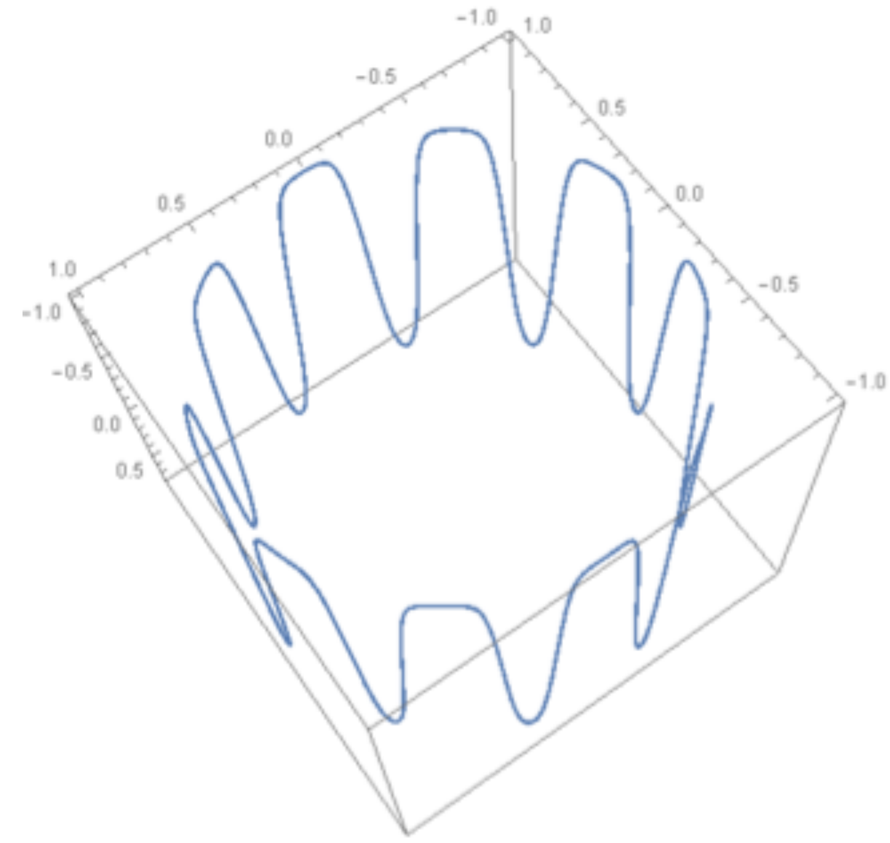
Complexity defines how much information is possibly coded.

The complexity of dynamics is often estimated by linear methods.

But these methods are blind to

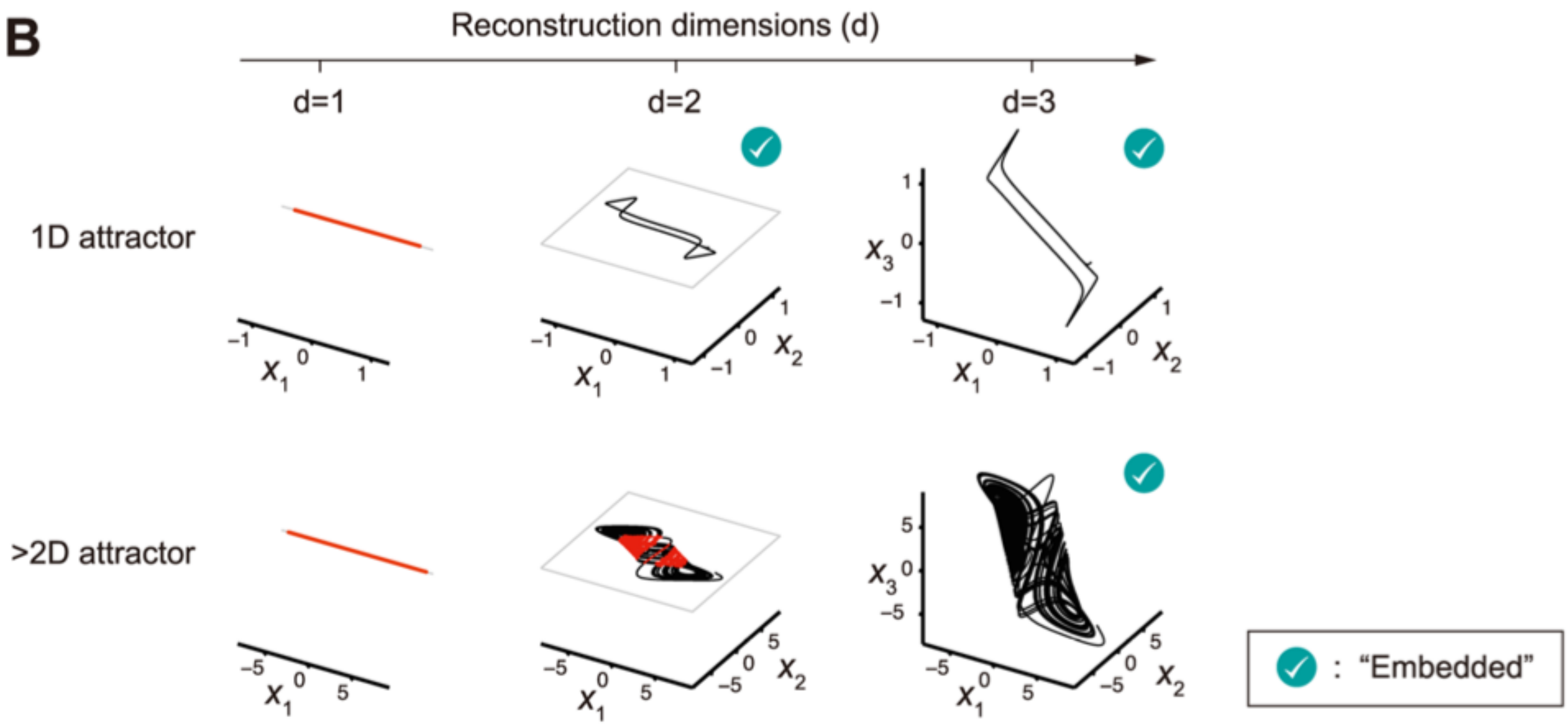
- Nonlinear features
- How the complexity is generated by network interactions.





Here, we develop a model-free, nonlinear method that can estimate fundamental dynamical complexity and show that it reveals information processing hierarchy.

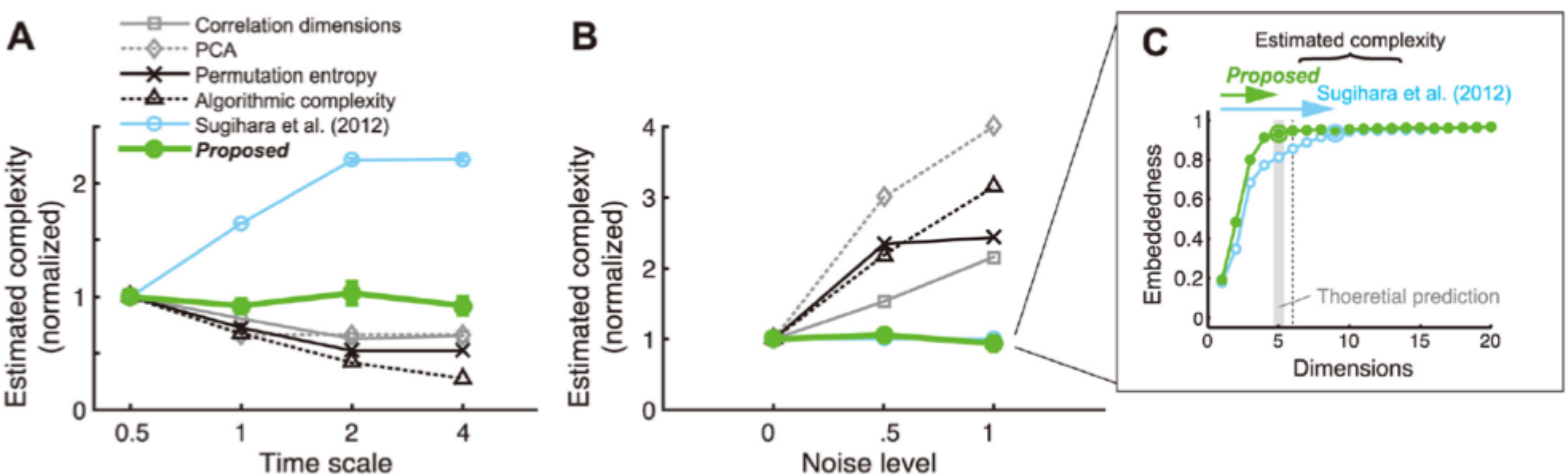
Use embedding for measuring dimensionality



Nice principle.
In practice, the estimated dimension is sensitive to the time bin.

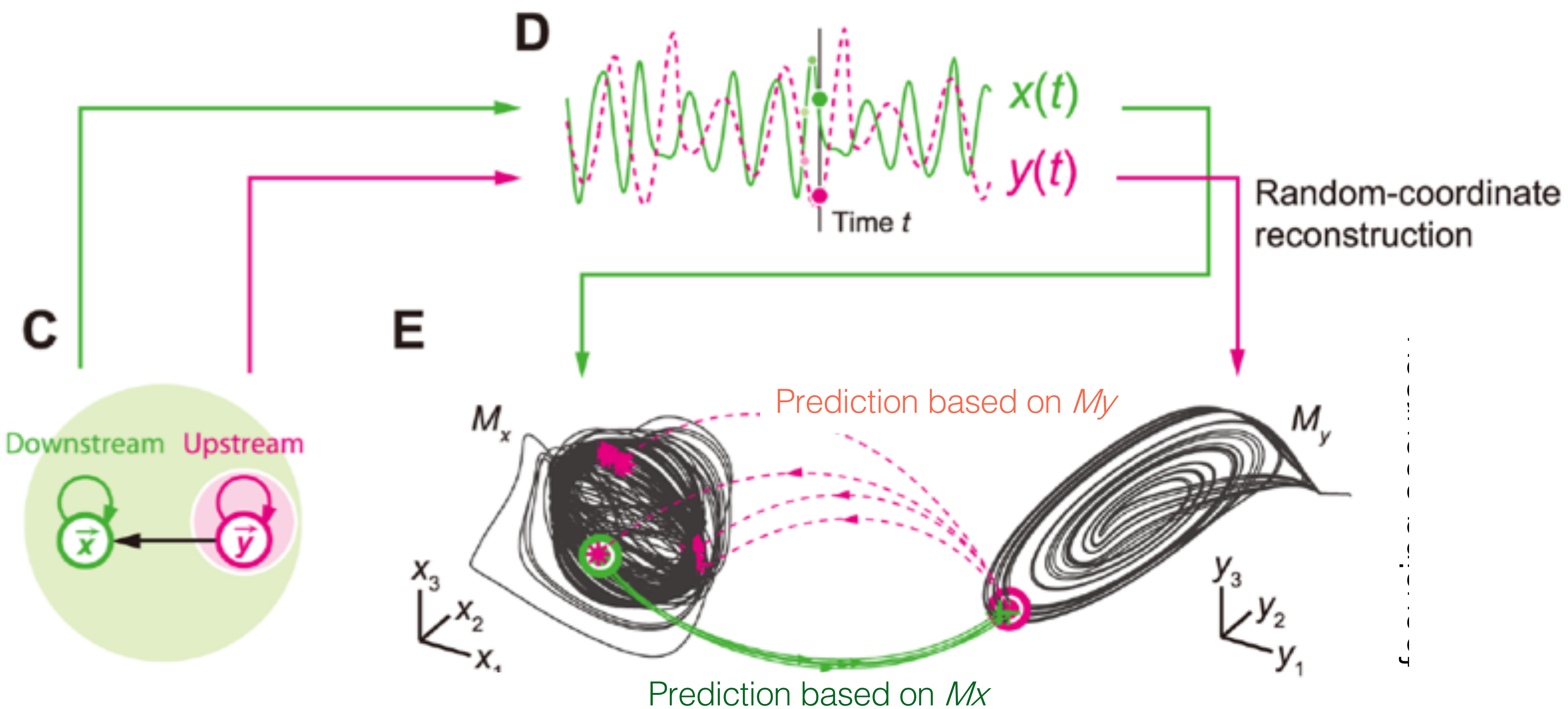
We propose a simple extension:
embedding timeseries in **randomized** delay coordinates.

This allows us to reliably estimate **complexity.**



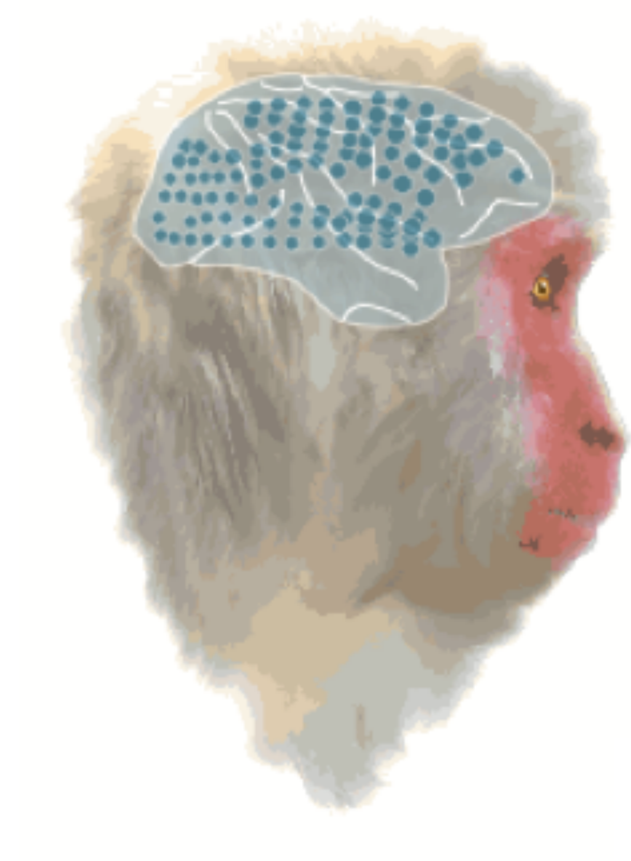
Cross-embedding with randomized delay coordinates: Complexity increases along information flow

Tajima et al. 2015

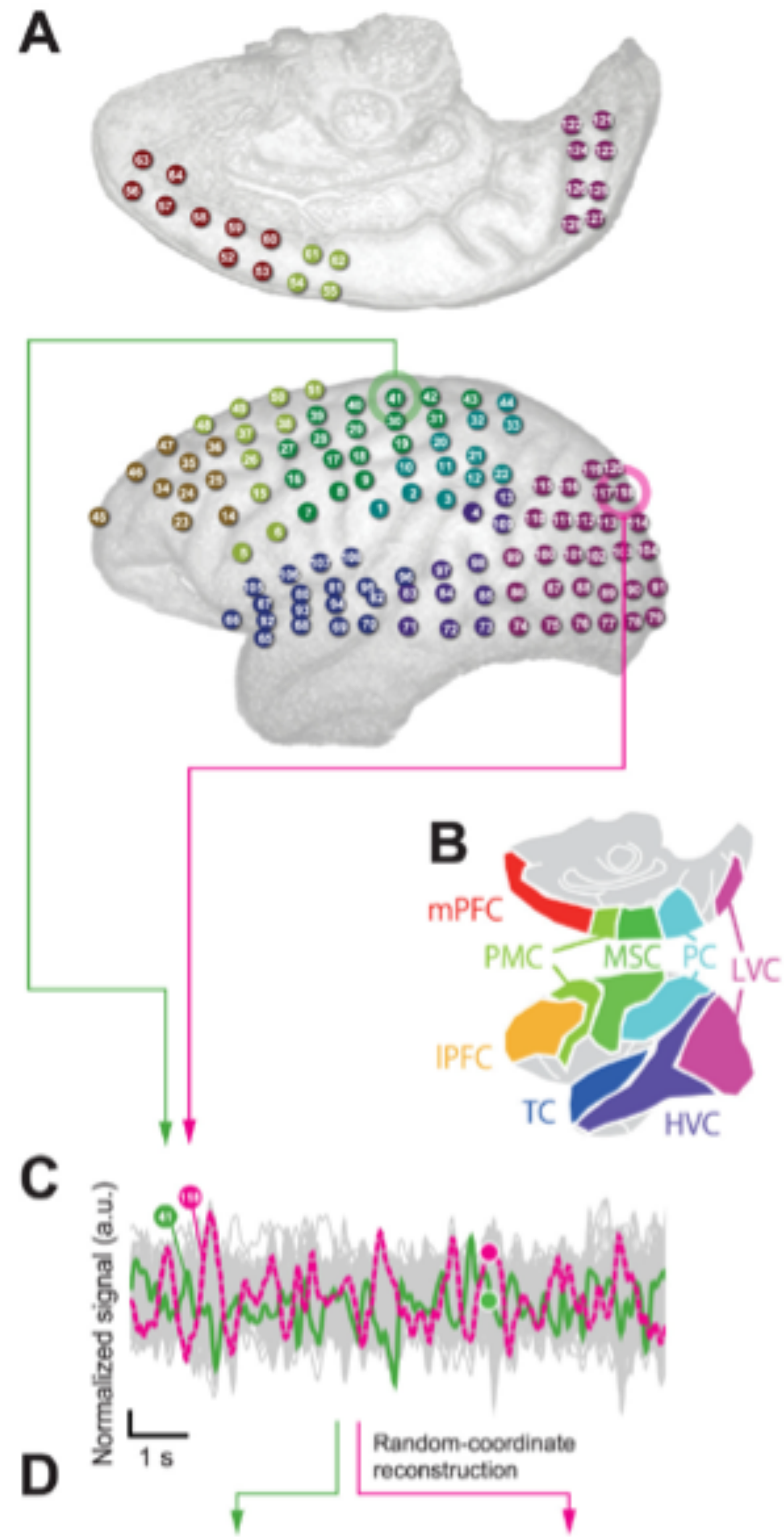


The downstream attractor must have higher dimensions than the upstream attractor.

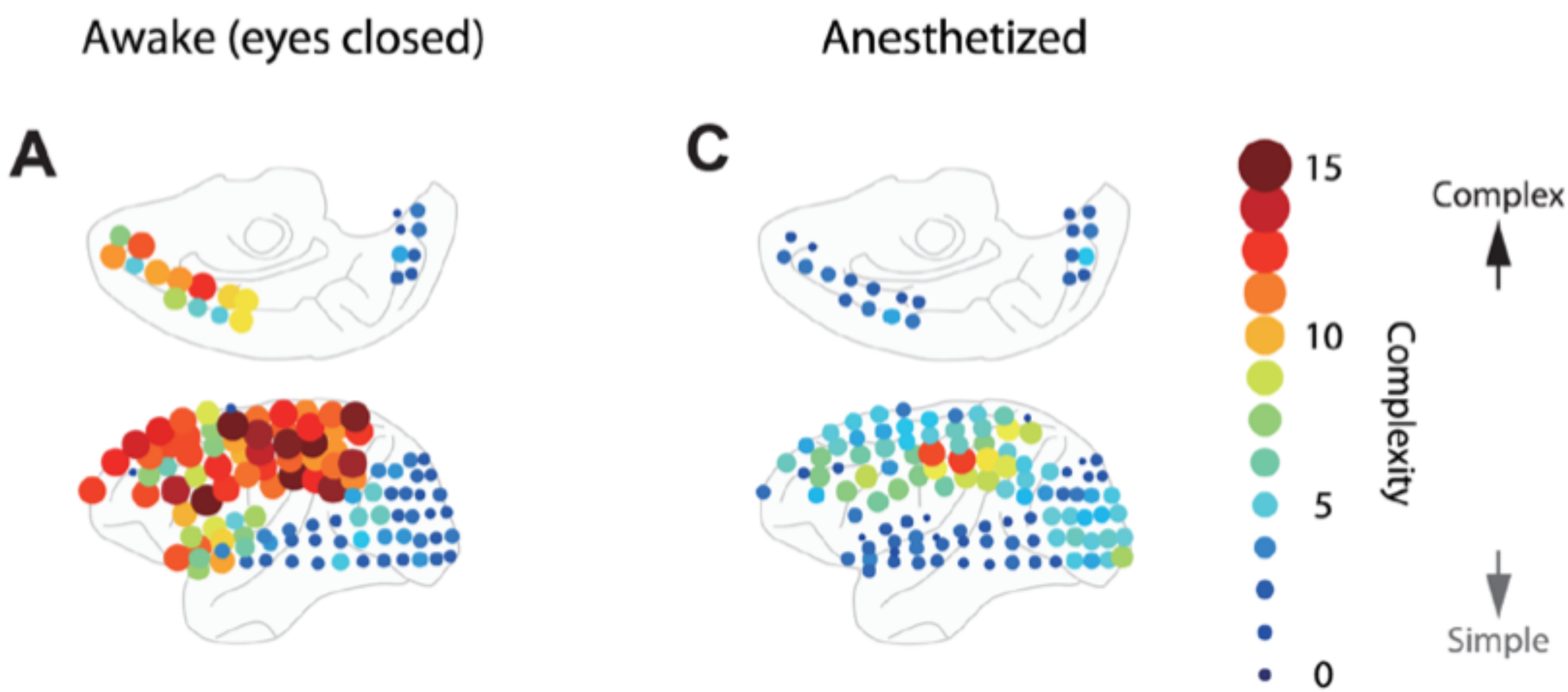
Large-scale ECoG recording from monkeys



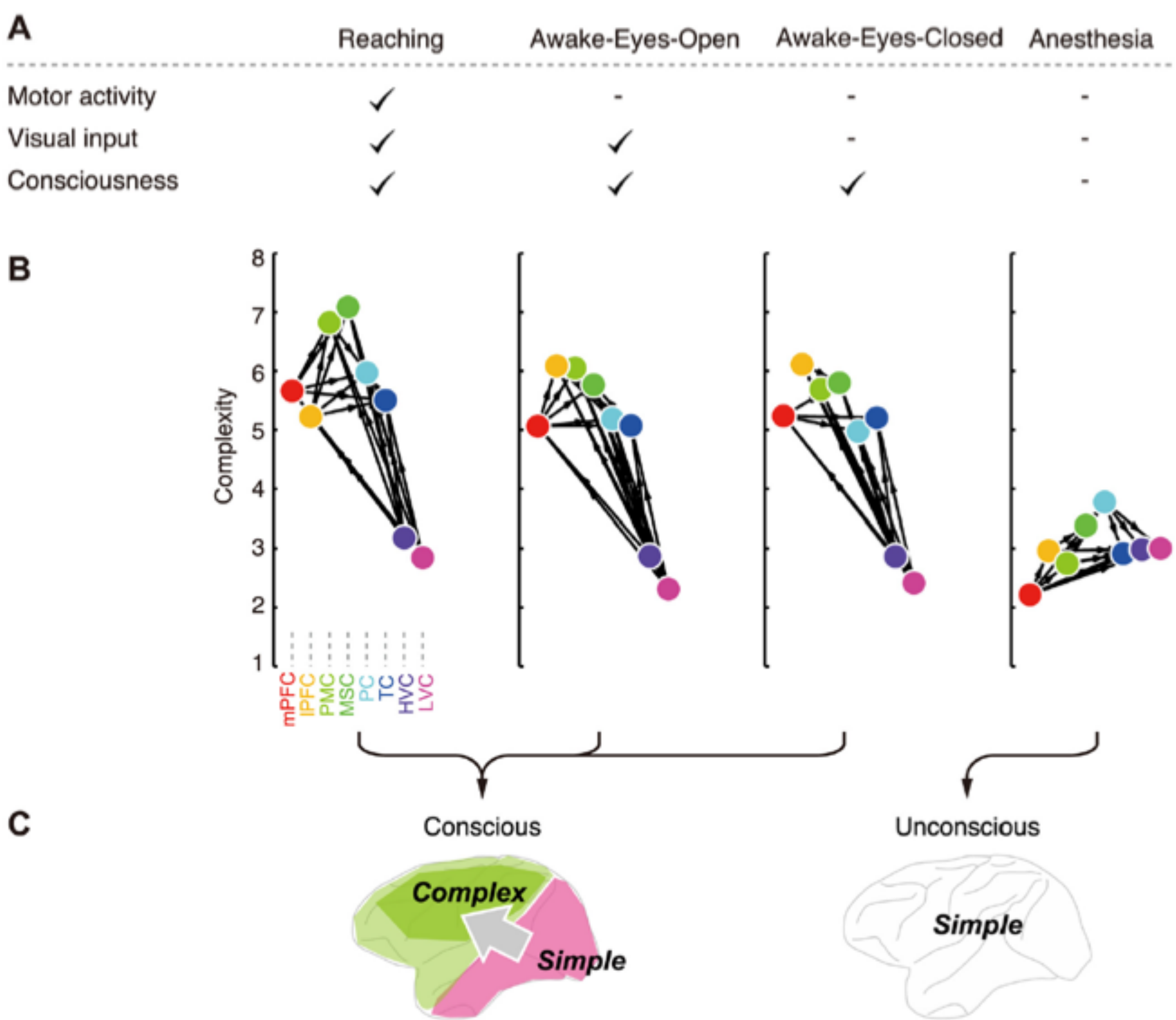
Yanagawa et al. 2013



The complexity of frontoparietal area was high during the awake state.



A hierarchy of cortical dynamics:
The complexity increases along cross-areal information flow



Tajima et al. 2015

Summary

- Our embedding method using randomized delay coordinates robustly extracts both dynamic complexity and information flow across brain regions.
- This approach reveals a new hierarchical organization of brain areas based on the dynamical complexity.
- We found that the frontoparietal areas are at the top of the hierarchical network during conscious states, concordant with anatomical integration of information over the entire brain.

Satohiro Tajima

1984-2017

Other collaborators

- Takeshi Mita (U. Tokyo)
- Hirokazu Takahashi (U. Tokyo)
- Douglas Bakkum (ETH)
- Toru Yanagawa (RIKEN BSI)
- Naotaka Fujii (RIKEN BSI)

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