# Unifying observables through latent dynamics
# Shared trajectories of brain, body, and behavior


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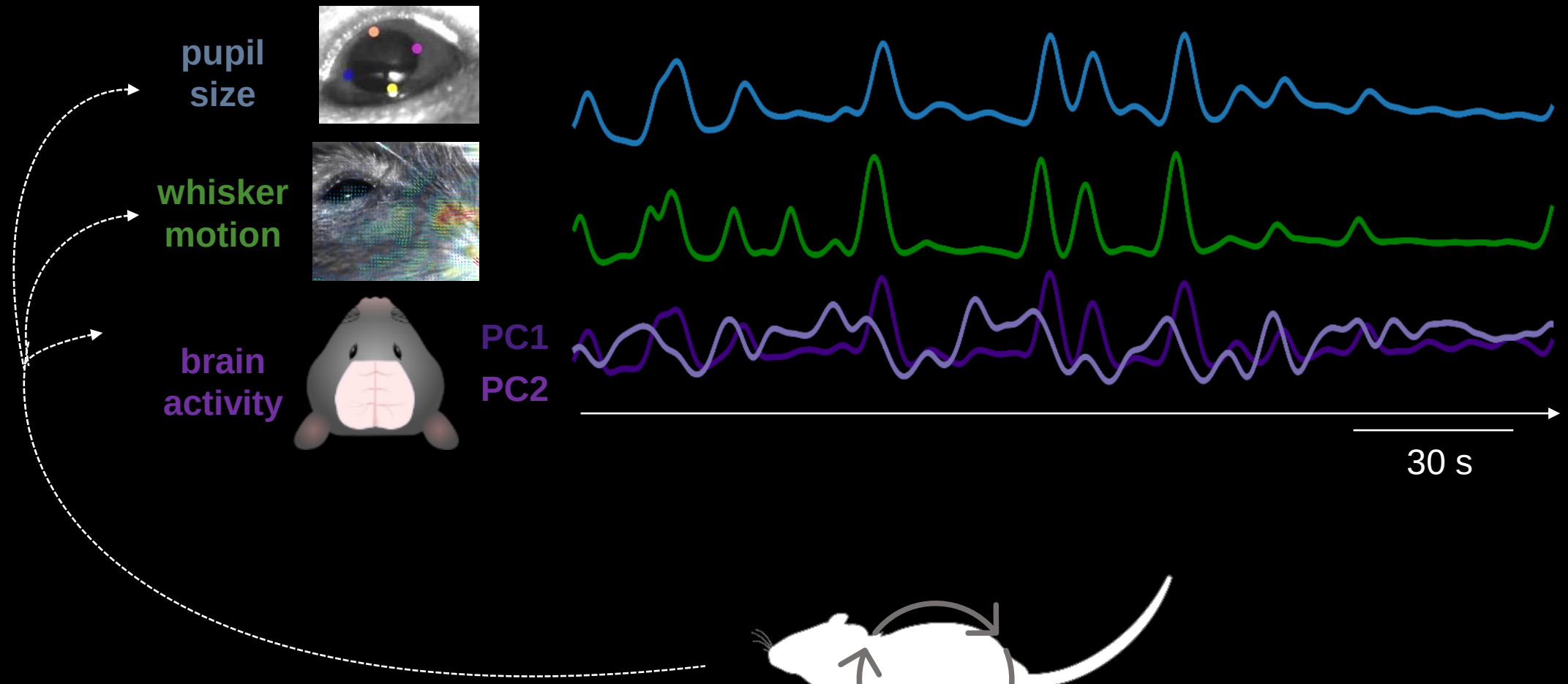
# Neuroscience: A problem in theory

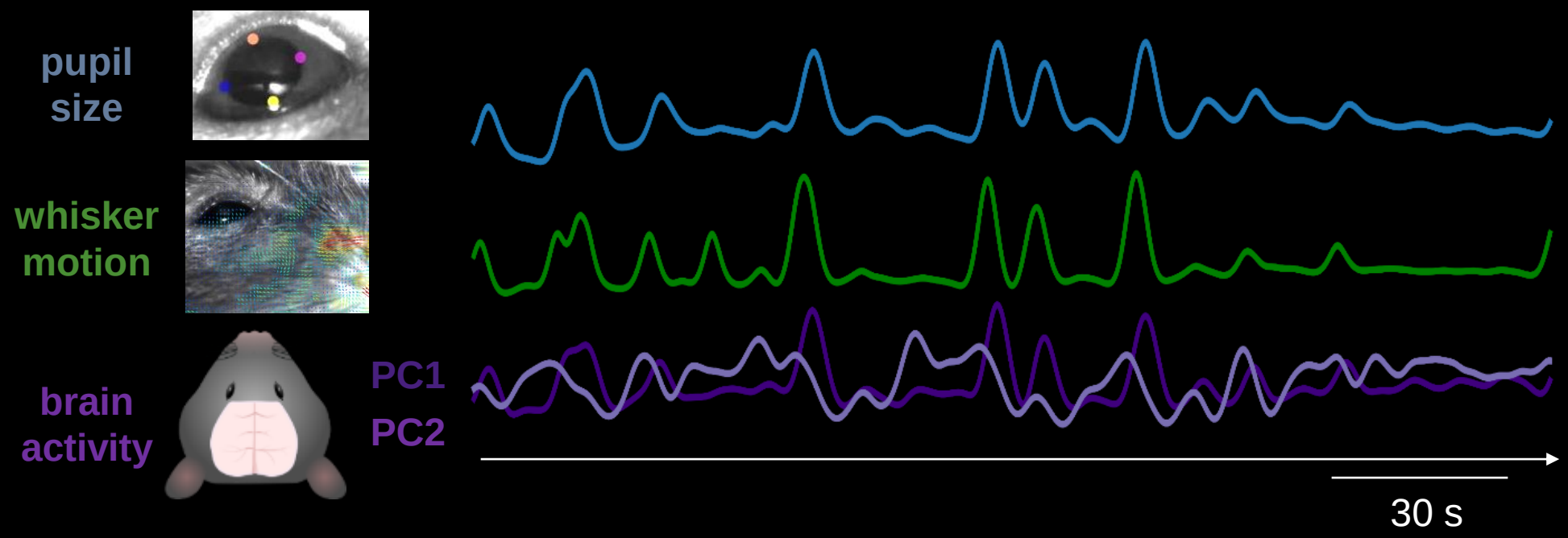
- **Problem:** Theoretical frameworks in neuroscience have limited ability to account for data
- **Alternative approach:** Address challenge by shifting emphasis from *predesignated* elements of brain/behavior to data-driven dynamical models
  - Seek reduced order models that can reconstruct observations
- **Goal:** In a minimally biased way, reveal intrinsic relationships between high-dimensional, multimodal observables and the lower-dimensional dynamical processes underlying them

# Challenges with complex systems

- High-dimensional…
- Feedback/circular causation…
- No governing laws…
- Don't know the "right" variables… (suboptimal coordinate system)
- Couldn't access them all anyway… (partial measurements)

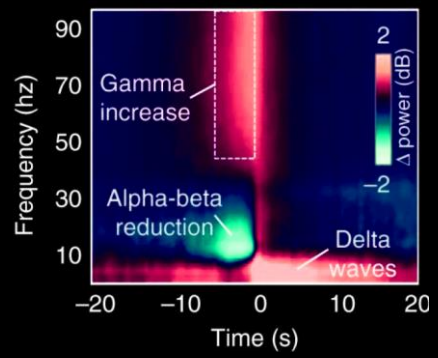
**How can we make progress in this setting?**
**Knowledge-based theory + data-driven analyses**


pupil size
whisker motion
brain activity
PC1
PC2
30 s



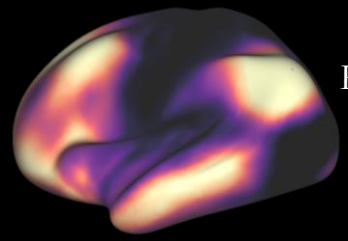

## Approach

1. **Theory-based approach to infer unobserved processes that interrelate known quantities**
2. Data-driven approach to identify the model form

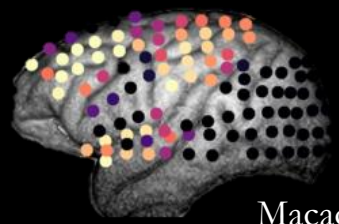



EEG oscillations

Liu et al. (2015) *Neuroimage*



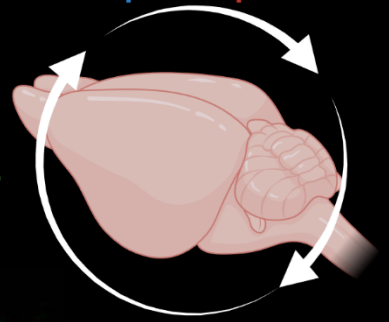
Human fMRI

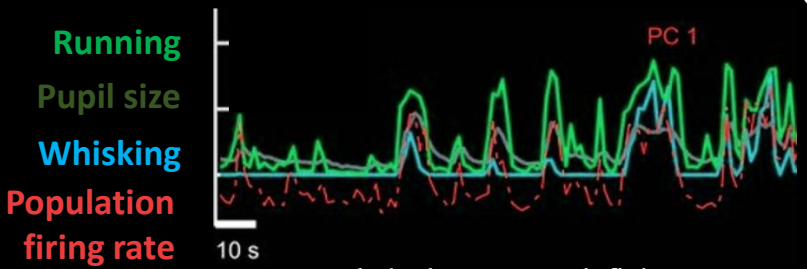


Macaque ECoG

brain networks

Raut et al. (2021) *Sci Adv*






global neuronal firing rates

Stringer, Pachitariu et al. (2019) *Science*

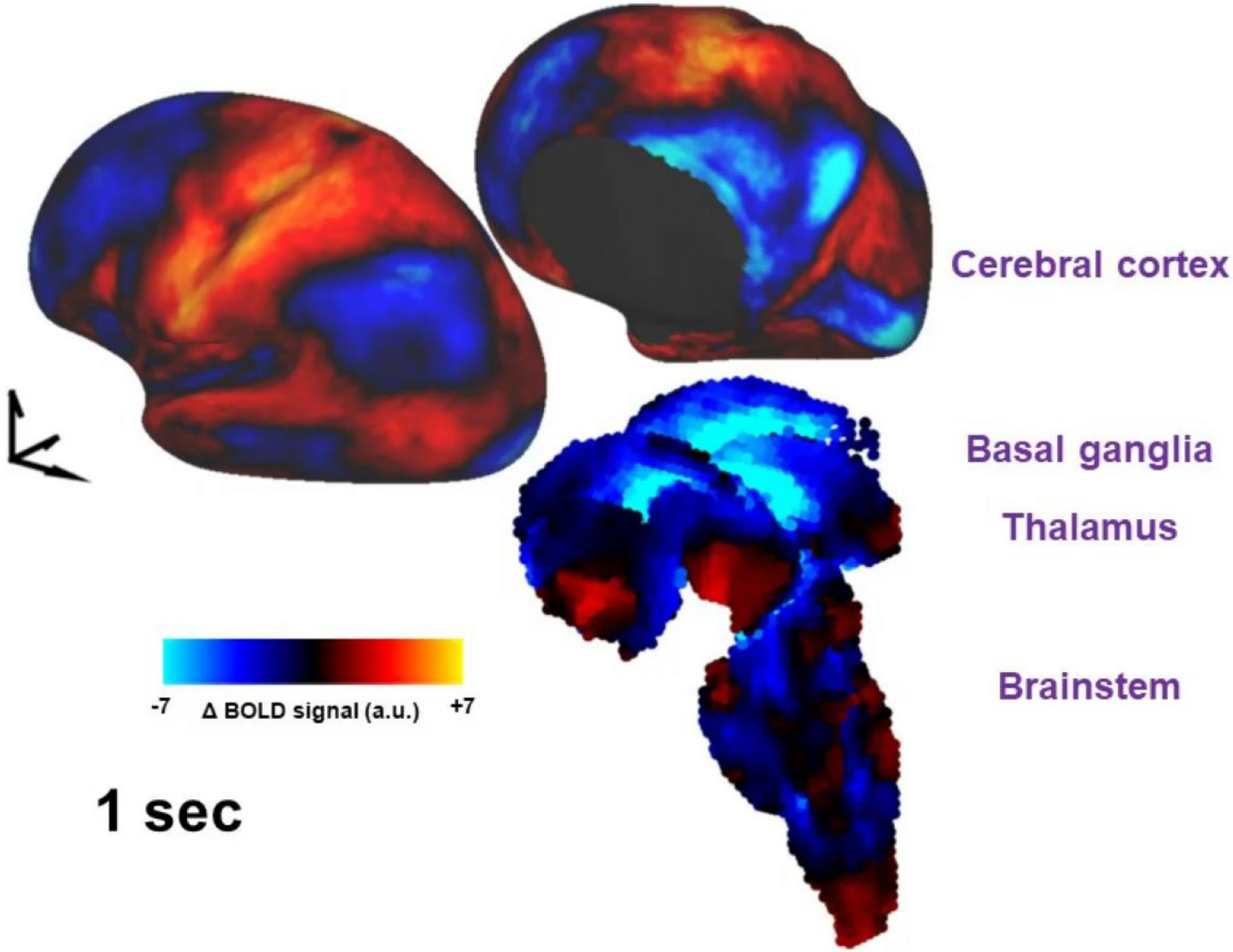

ionic environment

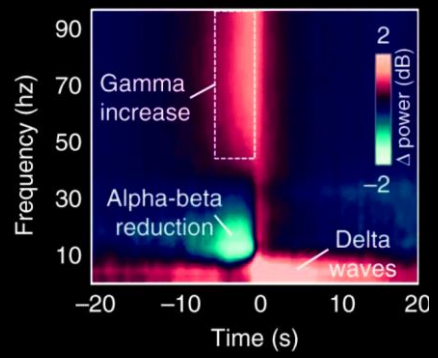
Rasmussen et al. (2020) *Prog Neurobiol*

# Global waves synchronize the brain's functional systems with fluctuating arousal

*Sci Adv* (2021)

Ryan V. Raut[1]*, Abraham Z. Snyder[1,2], Anish Mitra[3], Dov Yellin[4], Naotaka Fujii[5], Rafael Malach[4], Marcus E. Raichle[1,2]



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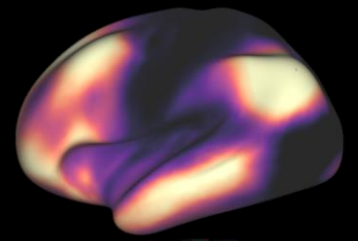

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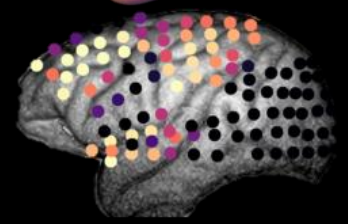
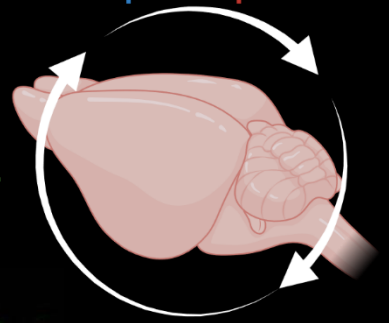
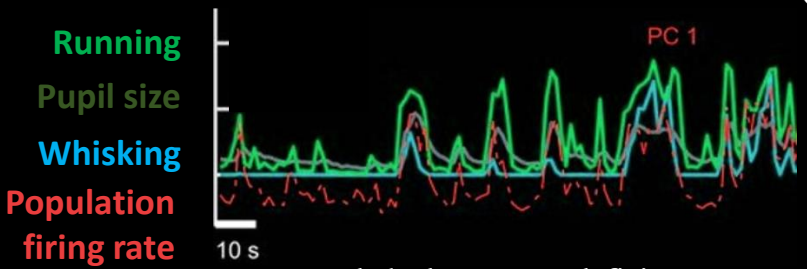


Macaque ECoG

spatial patterns

see Raut et al. (2021) *Sci Adv*



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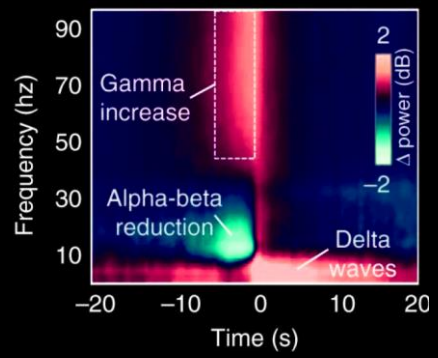


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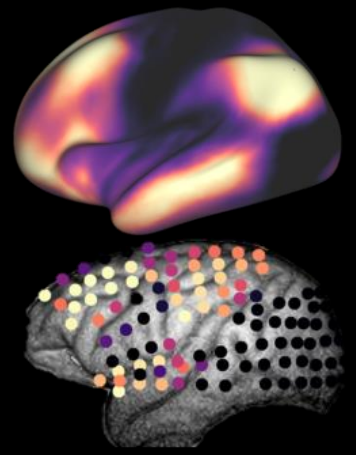

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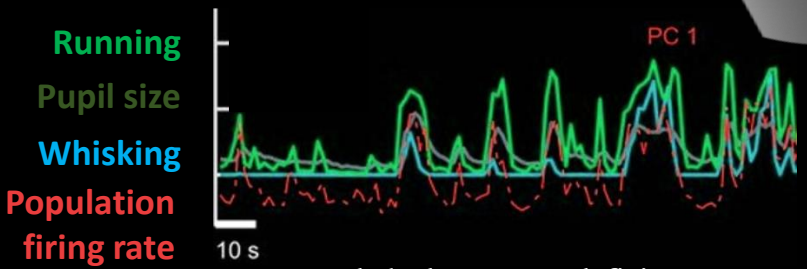


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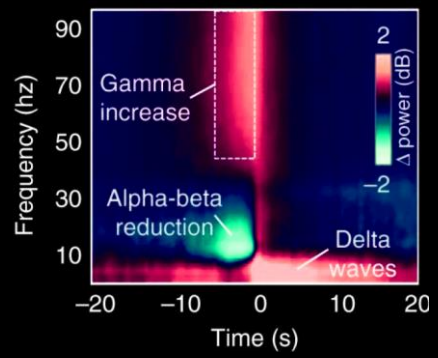
# Discovery problem: *Arousal as a process*

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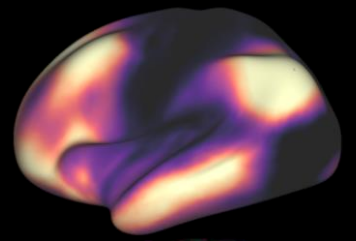

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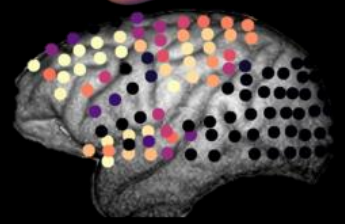

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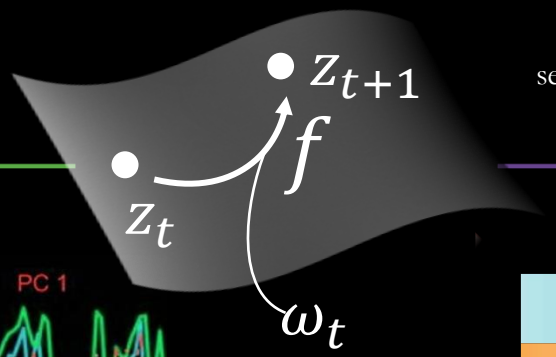


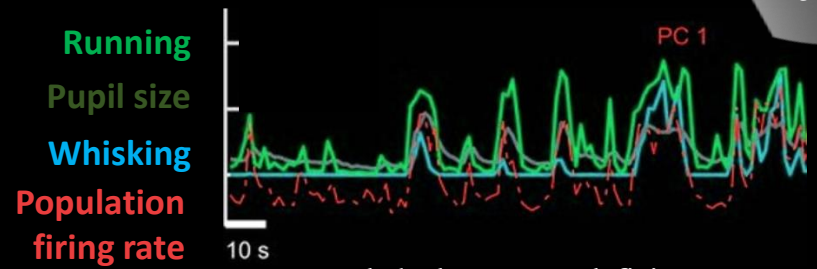


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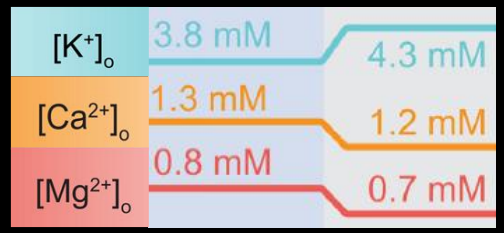


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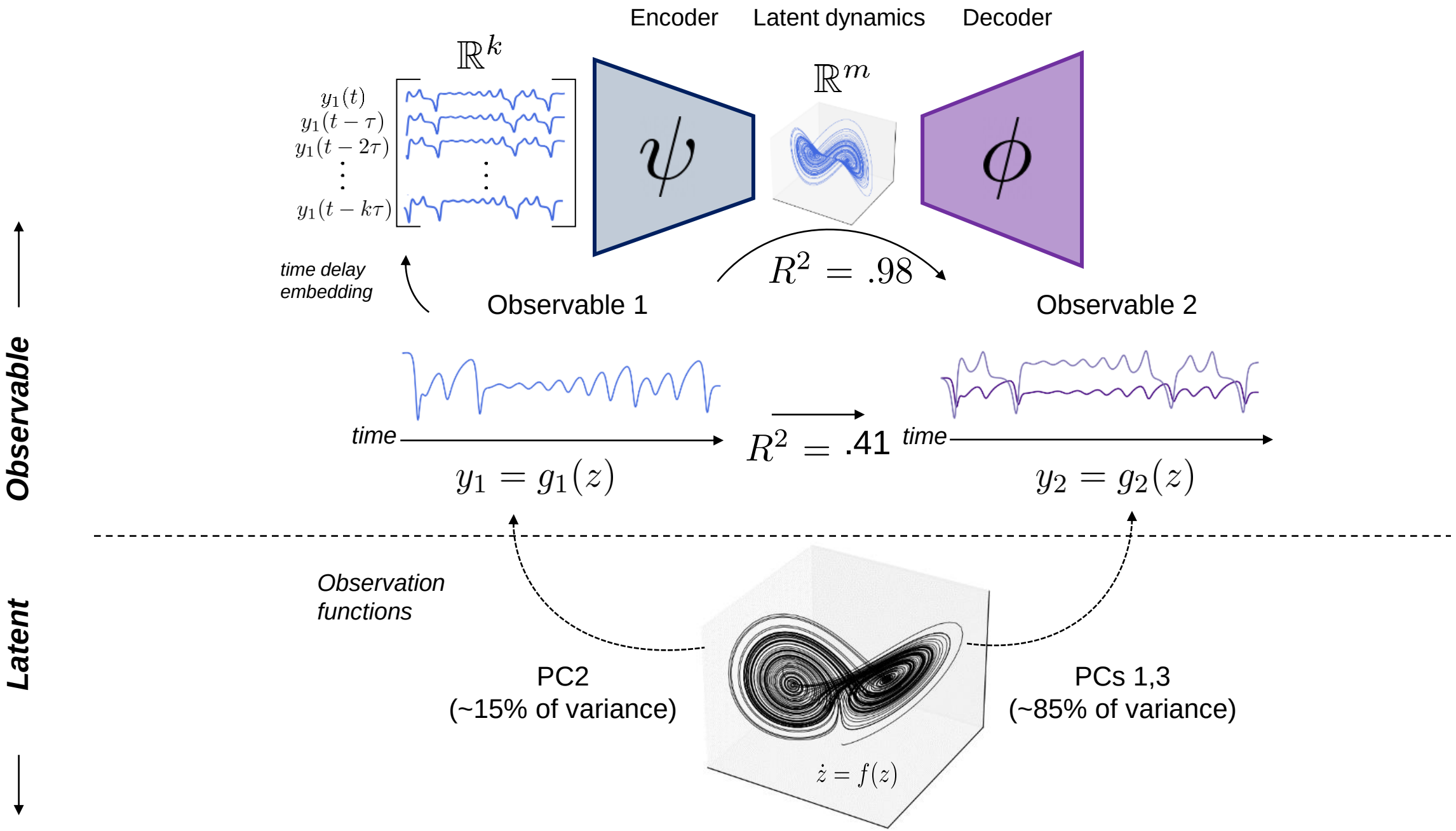
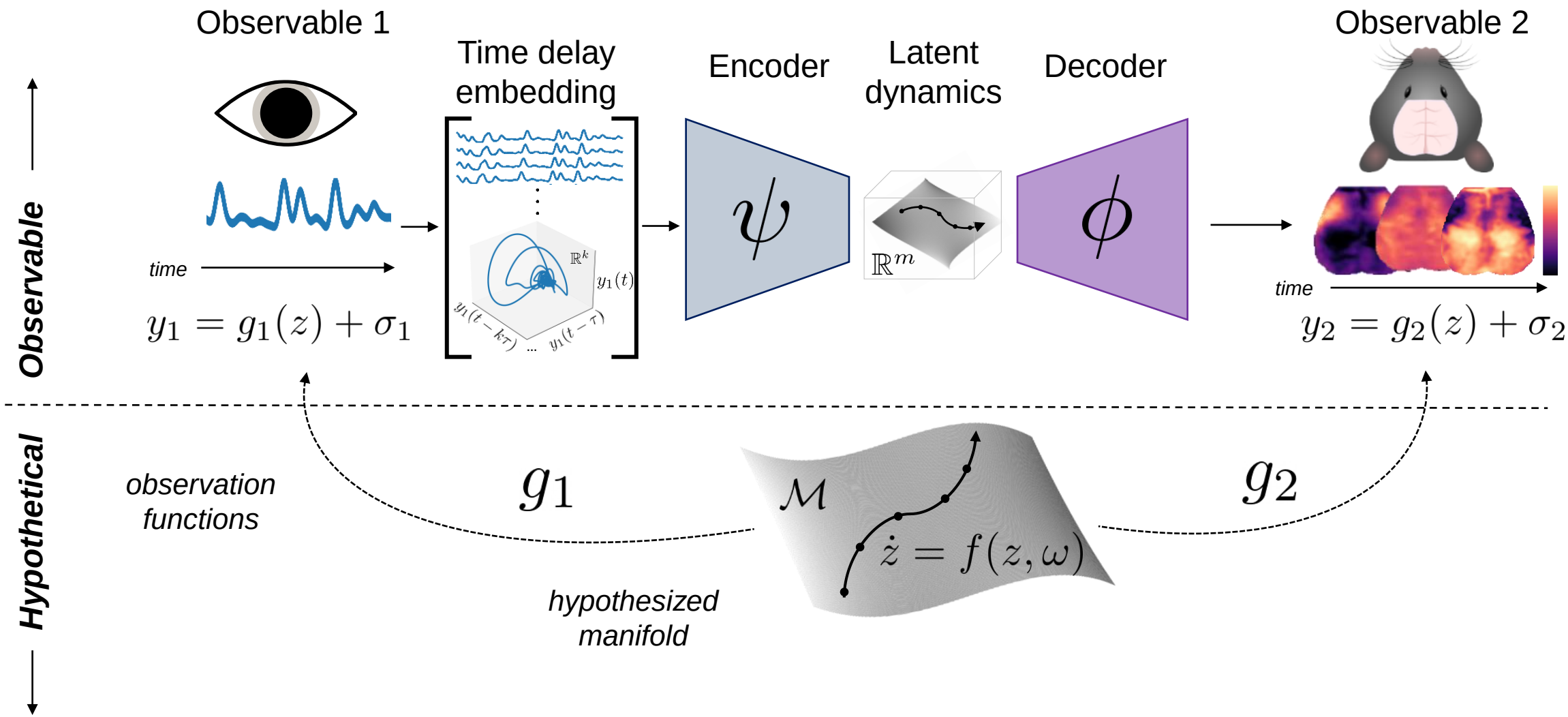
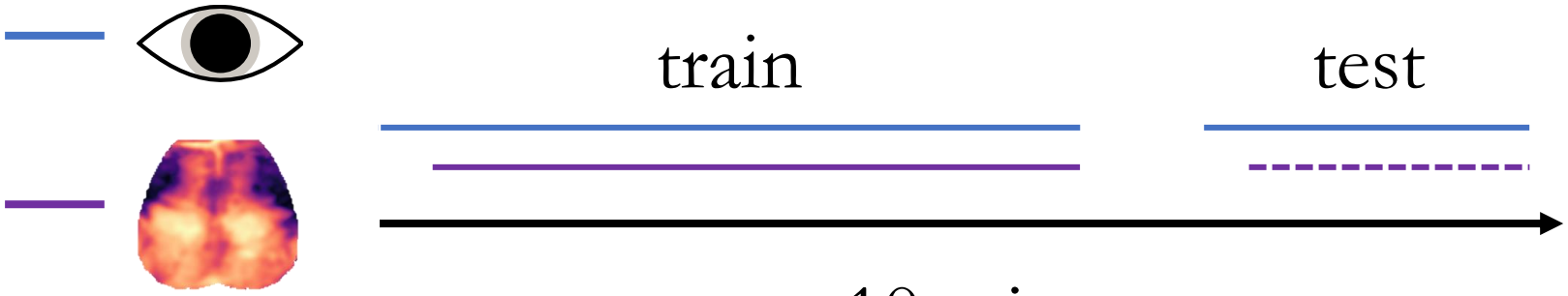

Encoder
Latent dynamics
Decoder
$\mathbb{R}^k$
$\mathbb{R}^m$
$y_1(t)$
$y_1(t-\tau)$
$y_1(t-2\tau)$
$y_1(t-k\tau)$
$\psi$
$\phi$
time delay embedding
$R^2 = .98$
Observable 1
Observable 2
time
$R^2 = .41$
time
$y_1 = g_1(z)$
$y_2 = g_2(z)$
Observable
Latent
Observation functions
PC2
(~15% of variance)
PCs 1,3
(~85% of variance)
$\dot{z} = f(z)$

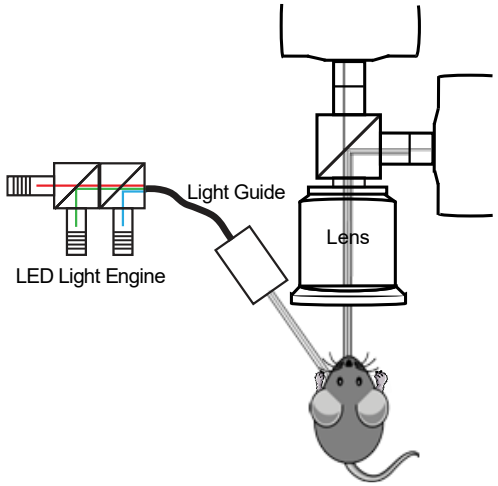
# Computational formulation



# Predicting WF from pupil



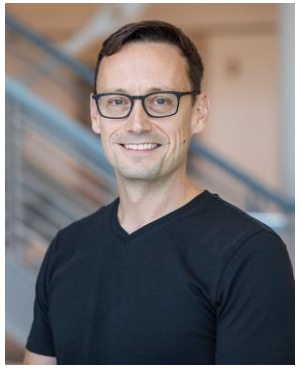

## Optical imaging




## Experimentalists


Zach Rosenthal


Xiaodan Wang


Adam Bauer

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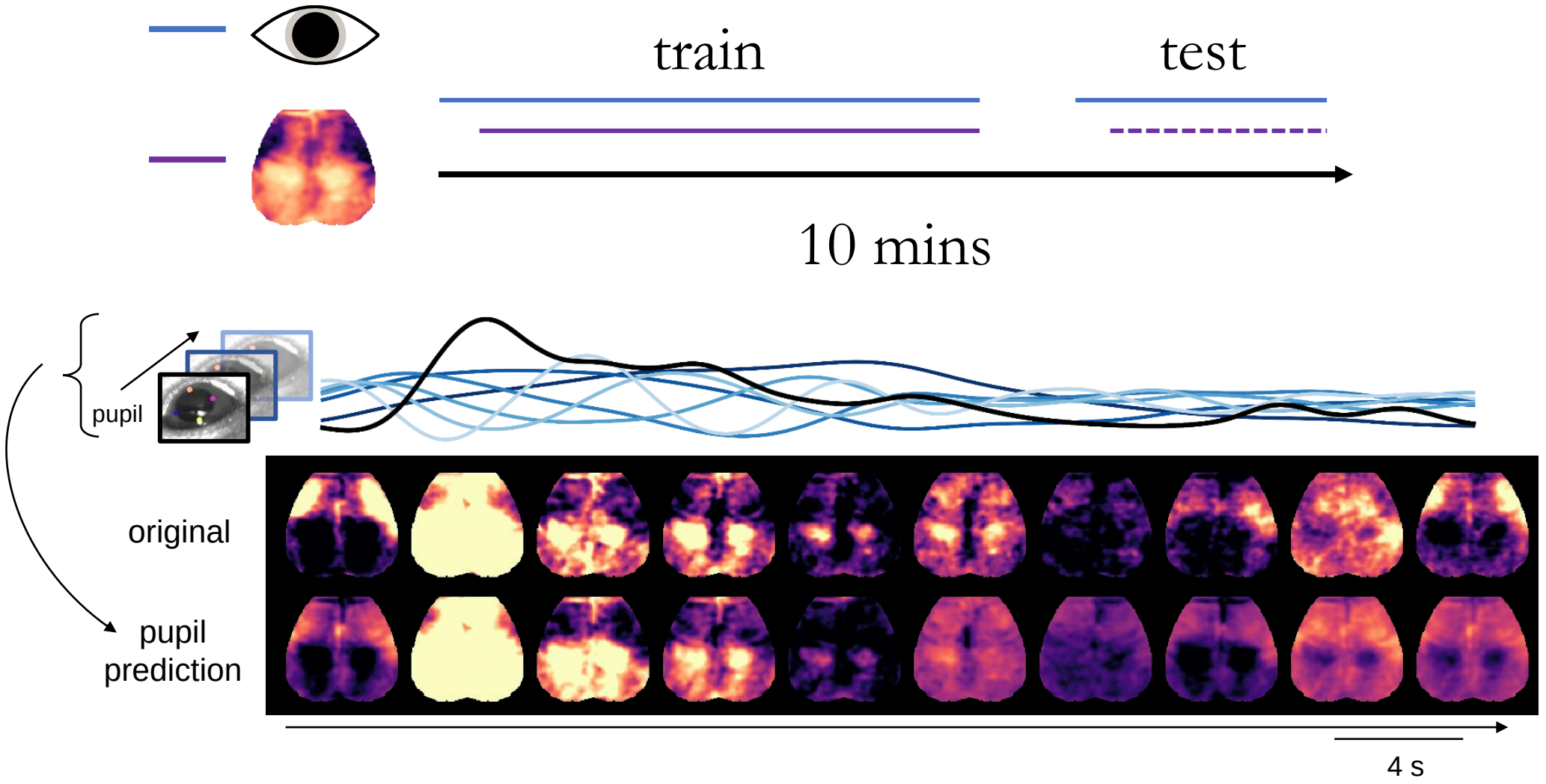

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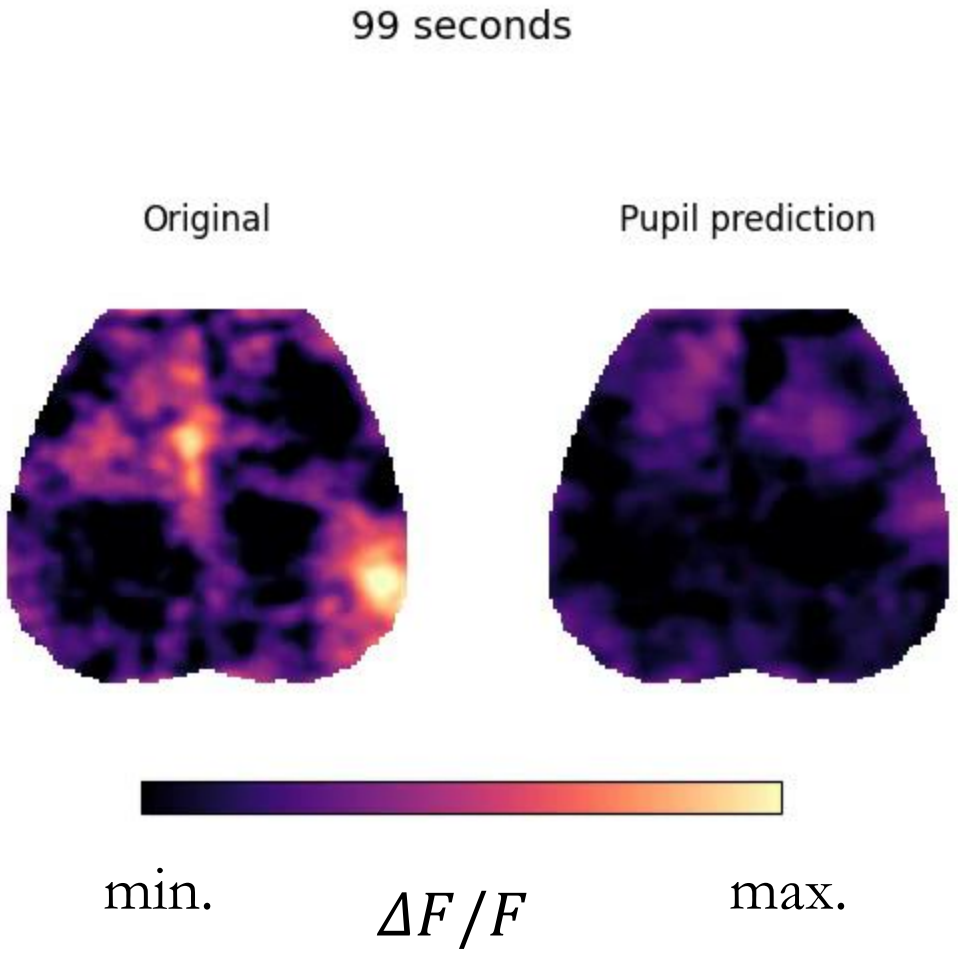

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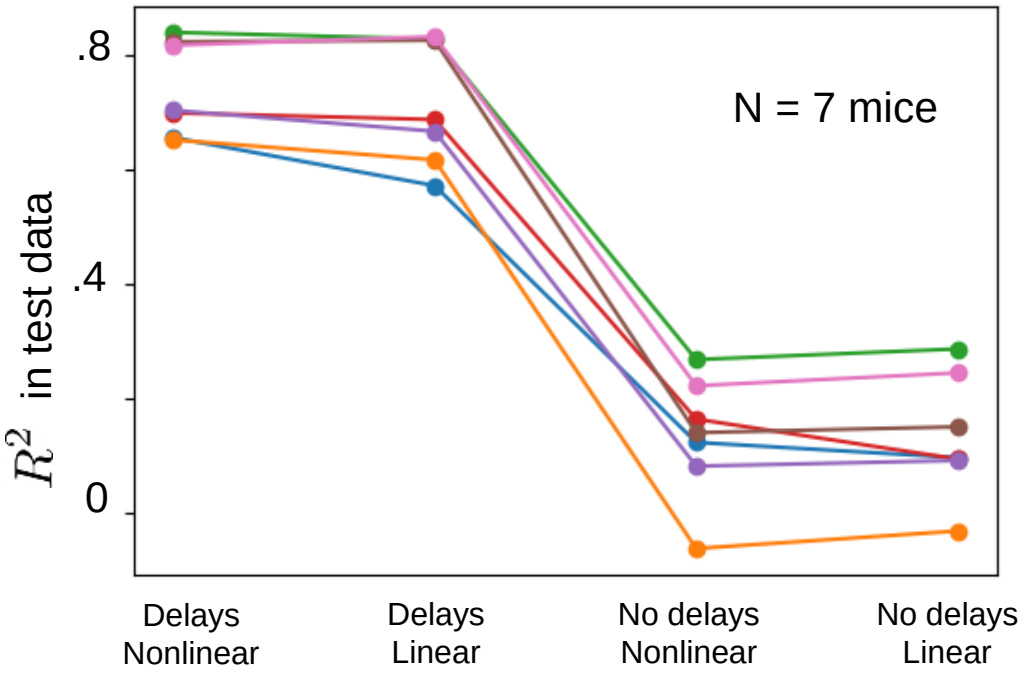
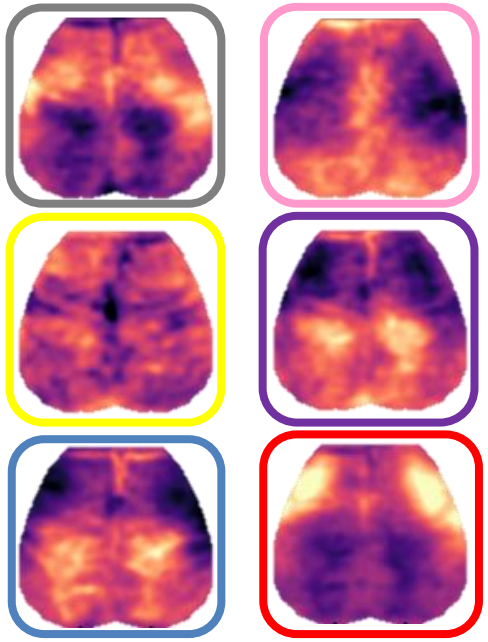


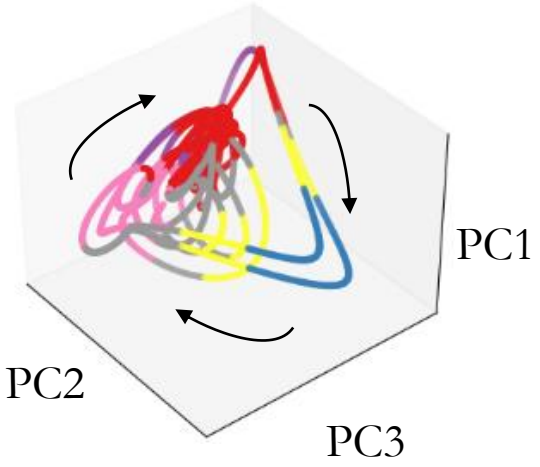
# Brain states segregate along an "arousal manifold"



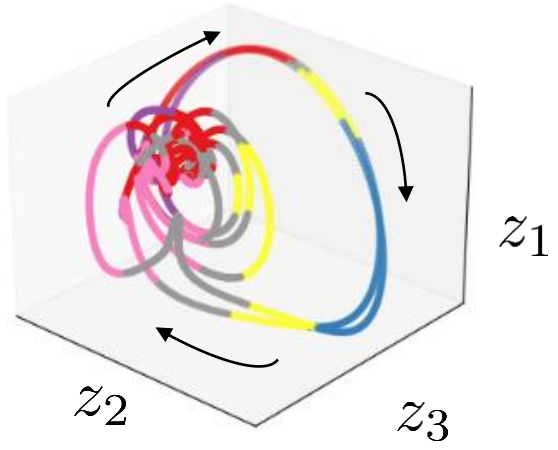
brain states

(*k*-means clustering applied to widefield image frames)

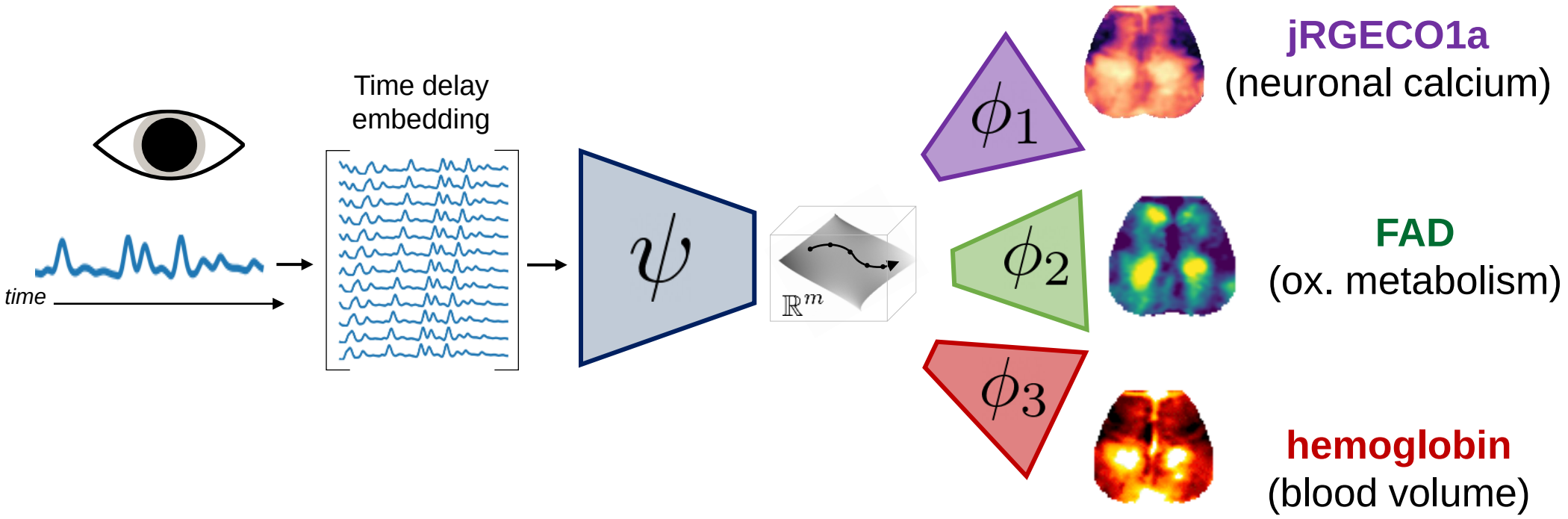
Trajectory in widefield PC coordinates




Trajectory in pupil delay coordinates



# Reconstruction from shared dynamics



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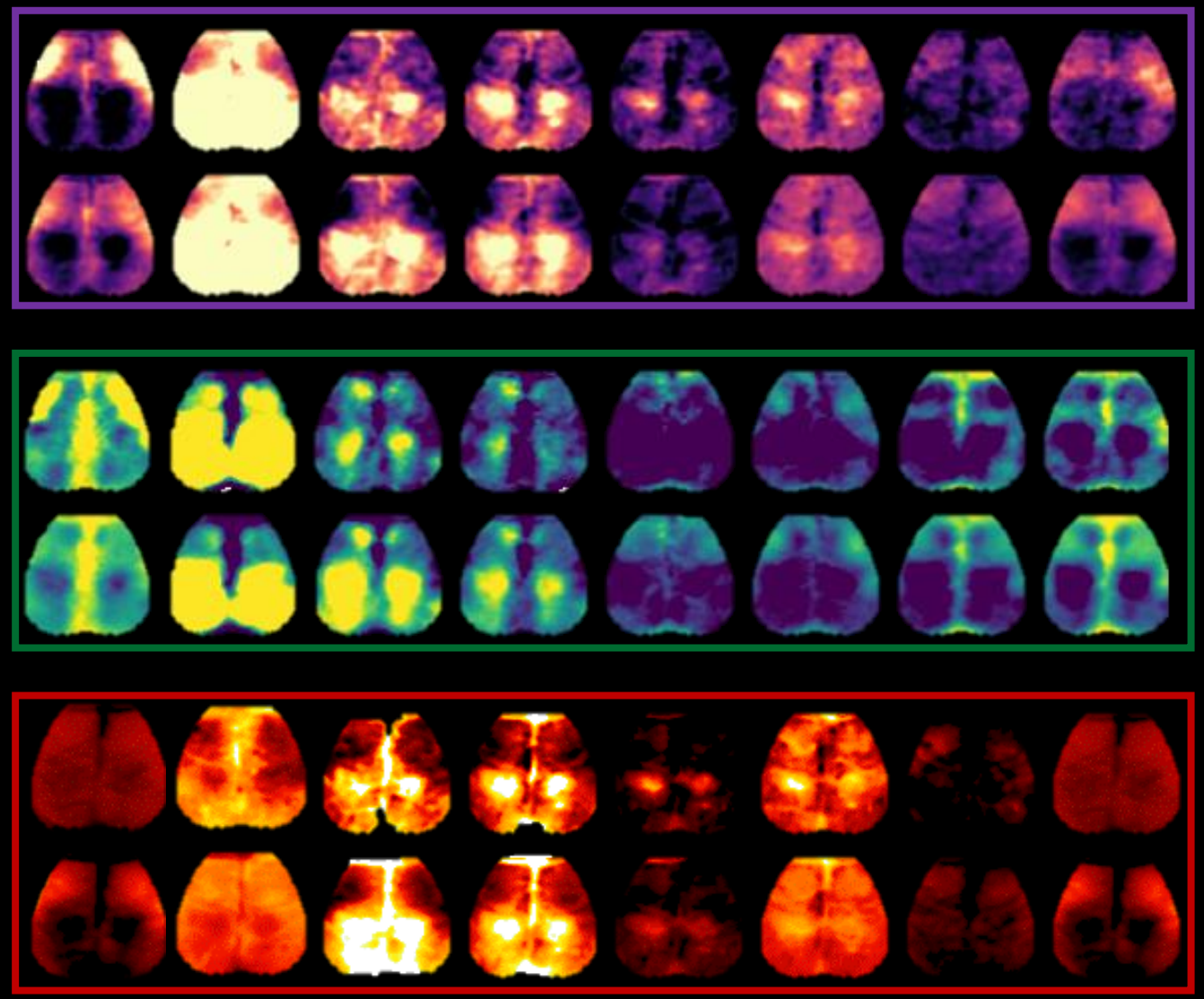
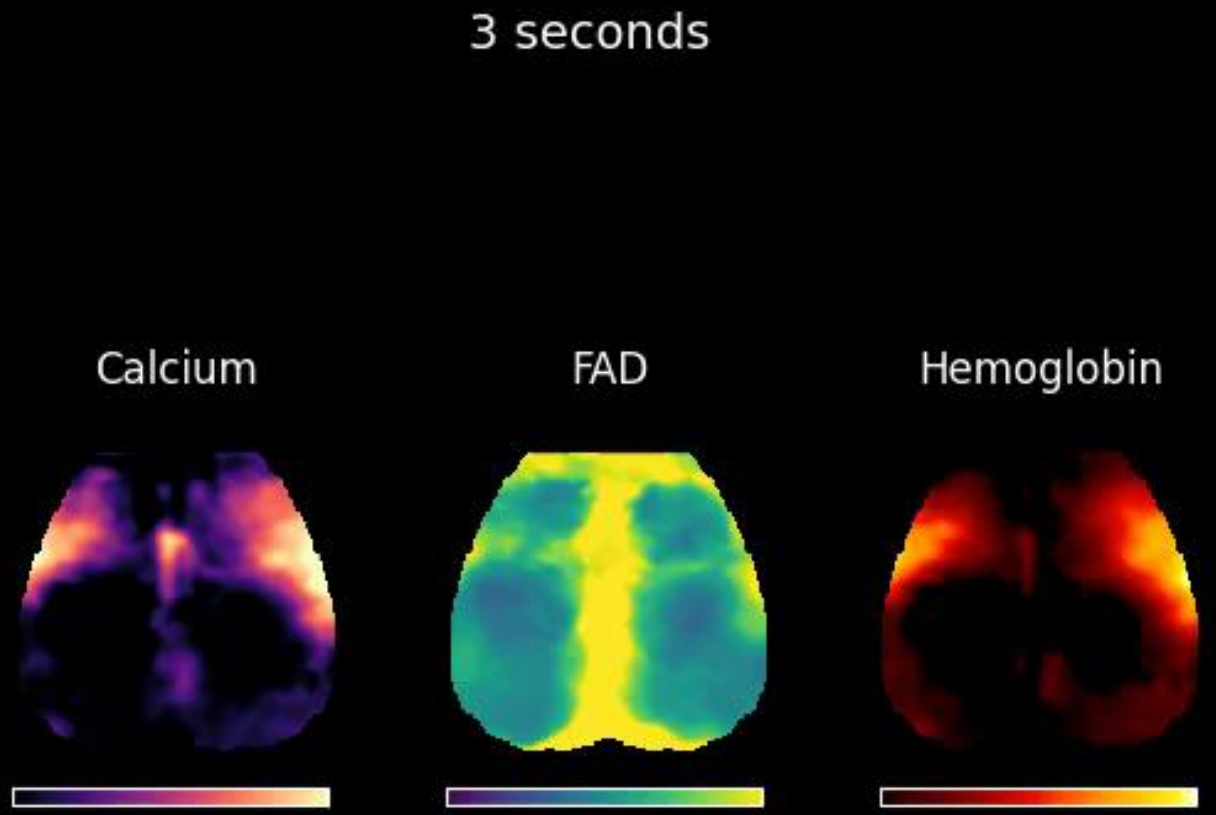


# Dynamical modeling



# Summary

- A data-driven framework for parsimoniously linking observations to a shared latent dynamical system
- Empirical support for a hypothesized arousal-related process underlying diverse measurements of interest across brain, body, behavior
- A combined theory-based and data-driven approach to brain and behavior based upon reduced-order modeling

# Thank you!

## Collaborators

### Computational/Theory

Nathan Kutz

Bing Brunton

Steve Brunton

UNIVERSITY of WASHINGTON

### Experimental

Zach Rosenthal

Xiaodan Wang

Adam Bauer

Washington University in St. Louis

## Funding

Shanahan Family Foundation

UNIVERSITY of WASHINGTON eScience Institute
ADVANCING DATA-INTENSIVE DISCOVERY IN ALL FIELDS

COMPUTATIONAL NEUROSCIENCE CENTER

ALLEN INSTITUTE

Questions / complaints? Please get in touch!
ryan.raut@alleninstitute.org